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DNA ENCODING A HUMAN BETAINE/GABA TRANSPORTER AND USES THEREOF

This application is a continuation of U.S. Serial No. 08/291,299, filed August 16, 1994, which is a continuation-in-part of U.S. Serial No. 08/001,738, filed January 4, 1993.

Background of the Invention

Throughout this application various publications are referred to by partial citations within parenthesis. Full citations for these publications may be found at the end of the specification immediately preceding the claims. The disclosures of these publications, in their entireties, are hereby incorporated by reference into this application in order to more fully describe the state of the art to which this invention pertains.

Cell surface transporters are critical to the survival and proper functioning of cells. Transporters serve in virtually all cells as the conduit by which essential nutrients such as glucose and amino acids gain access to the cell interior (for review see Silverman, 1991; Christensen, 1984). Transporters also play a critical role in the ability of cells to adapt to alterations in osmolarity. Within the nervous system transporters additionally serve a more specialized function. Specifically, high-affinity transporters are responsible for removing neurotransmitters from the synaptic cleft, thereby terminating neurotransmission (for review, see Kanner and Schuldiner, 1987).

The application of molecular biological techniques to the study of neurotransmitter transporters has greatly advanced our understanding of this class of proteins. Clones have now been obtained for many of the major

neurotransmitters including γ -aminobutyric acid (GABA) (Guastella et al., 1990; Nelson et al., 1990; Borden et al., 1992; Liu et al., 1992a), glycine (Smith et al., 1992a; Guastella et al., 1992; Liu et al., 1992b), norepinephrine (Pacholczyk et al., 1991), dopamine (Shimada et al., 1991; Usdin et al., 1991; Giros et al., 1992), and serotonin (Hoffman et al., 1991; Blakely et al., 1991).

Transporters have also been obtained for molecules with presumed neuromodulatory roles, such as taurine (Smith et al., 1992b; Uchida et al., 1992) and proline (Fremeau, Jr. et al., 1992). These transporters have in common a requirement for sodium and chloride, and they show considerable structural similarity including 12 putative transmembrane domains. More recently clones have been obtained that encode glutamate transporters unrelated to the others, perhaps consistent with their different ionic requirements (for review, see Amara, 1992).

Cloning of GABA transporters has revealed considerable diversity of this system. In addition to the original GABA transporter clone obtained from rat brain (GAT-1; Guastella et al., 1990), we have identified two additional rat brain clones encoding high-affinity GABA transporters which we term GAT-2 and GAT-3 (Borden et al., 1992). A clone identical to GAT-3 was described by Clark et al. (1992) and referred to as GAT-B, and the mouse homologues of all three transporters have been described (Liu et al., 1993); although a different nomenclature was employed. An additional and unanticipated member of this class is a betaine transporter, cloned from MDCK dog kidney cells by Handler and coworkers (Yamauchi et al., 1992). Betaine

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is an important osmolyte in the kidney, and possibly other organs. Interestingly, this transporter was found to have higher affinity for GABA than for betaine, suggesting a role in GABAergic transmission. However, transporter mRNA was not detected in dog brain (Yamauchi et al., 1992). Subsequently, Lopez-Corcuera et al. (1992) isolated from mouse brain a cDNA clone which displays both sequence and pharmacological similarity to the dog kidney clone. We now report the cloning and expression of a related clone from a human brain cDNA library. Although the function of this transporter in the nervous system is not understood, it may serve to regulate both GABAergic transmission and osmolarity.

To further characterize the human BGT-1 transporter, we have determined which of the cloned GABA transporters (e.g. GAT-1, GAT-2, GAT-3 and BGT) are in neurons and which are in glia, we have undertaken a combined pharmacological and molecular biological study using cell cultures derived from rat brain. We have also determined the specificity of four lipophilic GABA transport inhibitors for the cloned GABA transporters.

Summary of the Invention

This invention provides an isolated nucleic acid molecule encoding a mammalian betaine/GABA transporter. In one embodiment of this invention the isolated nucleic acid molecule encodes a human betaine/GABA transporter. In another embodiment of this invention, the nucleic acid molecule encoding the human betaine/GABA transporter comprises a plasmid designated pcEXV-hBGT (ATCC Accession No. 753193).

This invention provides a nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a unique sequence included within the sequence of a nucleic acid molecule encoding a mammalian betaine/GABA transporter. This invention also provides a nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a unique sequence included within the sequence of a nucleic acid molecule encoding a human betaine/GABA transporter.

This invention further provides an antisense oligonucleotide having a sequence capable of binding specifically to an mRNA molecule encoding a mammalian betaine/GABA transporter so as to prevent translation of the mRNA molecule. This invention also provides an antisense oligonucleotide having a sequence capable of binding specifically to an mRNA molecule encoding a human betaine/GABA transporter so as to prevent translation of the mRNA molecule.

This invention provides a monoclonal antibody directed to a mammalian betaine/GABA transporter. This invention further provides a monoclonal antibody directed to a human betaine/GABA transporter.

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This invention provides a pharmaceutical composition comprising an amount of a substance effective to alleviate the abnormalities resulting from overexpression of a mammalian betaine/GABA transporter and a pharmaceutically acceptable carrier as well as a pharmaceutical composition comprising an amount of a substance effective to alleviate abnormalities resulting from underexpression of betaine/GABA transporter and a pharmaceutically acceptable carrier.

10 A pharmaceutical composition comprising an amount of a substance effective to alleviate the abnormalities resulting from overexpression of a human betaine/GABA transporter and a pharmaceutically acceptable carrier as well as a pharmaceutical composition comprising an amount of a substance effective to alleviate abnormalities resulting from underexpression of a human betaine/GABA transporter and a pharmaceutically acceptable carrier is also provided by this invention.

20 This invention also provides a transgenic, nonhuman mammal whose genome comprises DNA encoding a mammalian betaine/GABA transporter so positioned within such genome as to be transcribed into antisense mRNA complementary to mRNA encoding the betaine/GABA transporter and when hybridized to mRNA encoding the betaine/GABA transporter, the complementary mRNA reduces the translation of the mRNA encoding the betaine/GABA transporter.

30 This invention also provides a transgenic, nonhuman mammal whose genome comprises DNA encoding a human betaine/GABA transporter so positioned within such genome as to be transcribed into antisense mRNA which is complementary to mRNA encoding the human betaine/GABA transporter and when hybridized to mRNA encoding the human betaine/GABA transporter, the

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antisense mRNA thereby reduces the translation of mRNA encoding the human betaine/GABA transporter.

5 This invention also provides a transgenic, nonhuman mammal whose genome comprises DNA encoding a mammalian betaine/GABA transporter so positioned within such genome as to be transcribed into antisense mRNA which is complementary to mRNA encoding the transporter and when hybridized to mRNA encoding the transporter, the antisense mRNA thereby prevents the translation of mRNA encoding the transporter.

10 This invention also provides a transgenic, nonhuman mammal whose genome comprises DNA encoding a human betaine/GABA transporter so positioned within such genome as to be transcribed into antisense mRNA which is complementary to mRNA encoding the betaine/GABA transporter and when hybridized to mRNA encoding the betaine/GABA transporter, the antisense mRNA thereby prevents the translation of mRNA encoding the human betaine/GABA transporter.

15 This invention provides a method of screening drugs to identify drugs which specifically interact with, and bind to, a mammalian betaine/GABA transporter on the surface of a cell which comprises contacting a mammalian cell comprising an isolated DNA molecule encoding a mammalian betaine/GABA transporter, the protein encoded thereby is expressed on the cell surface, with a plurality of drugs, determining those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, a mammalian betaine/GABA transporter.

20 This invention provides a method of screening drugs to identify drugs which specifically interact with, and bind to, a human betaine/GABA transporter on the

surface of a cell which comprises, contacting a mammalian cell comprising an isolated DNA molecule encoding a human betaine/GABA transporter, the protein encoded thereby is expressed on the cell surface, with a plurality of drugs, determining those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, a human betaine/GABA transporter.

This invention also provides a method of determining the physiological effects of expressing varying levels of a mammalian betaine/GABA transporter which comprises producing a transgenic nonhuman animal whose levels of mammalian betaine/GABA transporter expression are varied by use of an inducible promoter which regulates mammalian betaine/GABA transporter expression.

This invention also provides a method of determining the physiological effects of expressing varying levels of a human betaine/GABA transporter which comprises producing a transgenic nonhuman animal whose levels of human betaine/GABA transporter expression are varied by use of an inducible promoter which regulates human betaine/GABA transporter expression.

This invention further provides a method of determining the physiological effects of expressing varying levels of a mammalian betaine/GABA transporter which comprises producing a panel of transgenic nonhuman animals each expressing a different amount of mammalian betaine/GABA transporter.

This invention further provides a method of determining the physiological effects of expressing varying levels of a human betaine/GABA transporter which comprises producing a panel of transgenic nonhuman animals each

expressing a different amount of human betaine/GABA transporter.

- 5 This invention provides a method for diagnosing a predisposition to a disorder associated with the expression of a specific mammalian betaine/GABA transporter allele which comprises: a.) obtaining DNA of subjects suffering from the disorder; b.) performing a restriction digest of the DNA with a panel of restriction enzymes; c.) electrophoretically separating the resulting DNA fragments on a sizing gel; d.) contacting the resulting gel with a nucleic acid probe capable of specifically hybridizing to 'DNA encoding a mammalian betaine/GABA transporter and labelled with a detectable marker; e.) detecting labelled bands which have hybridized to the DNA encoding a mammalian betaine/GABA transporter labelled with a detectable marker to create a unique band pattern specific to the marker to create a unique band pattern specific to the marker to create a unique band pattern specific to the disorder; f.) preparing DNA obtained for diagnosis by steps a-e; and g.) comparing the unique band pattern specific to the DNA of subjects suffering from the disorder from step e and the DNA obtained for diagnosis from step f to determine whether the patterns are the same or different and to diagnose thereby predisposition to the disorder if the patterns are the same.
- 10 15 20 25 30 35
- 10 This invention provides a method for diagnosing a predisposition to a disorder associated with the expression of a specific human betaine/GABA transporter allele which comprises: a.) obtaining DNA of subjects suffering from the disorder; b.) performing a restriction digest of the DNA with a panel of restriction enzymes; c.) electrophoretically separating the resulting DNA fragments on a sizing gel; d.) contacting the resulting gel with a nucleic acid probe
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capable of specifically hybridizing to DNA encoding a human betaine/GABA transporter and labelled with a detectable marker; e.) detecting labelled bands which have hybridized to the DNA encoding a human betaine/GABA transporter labelled with a detectable marker to create a unique band pattern specific to the DNA of subjects suffering from the disorder; f.) preparing DNA obtained for diagnosis by steps a-e; and g.) comparing the unique band pattern specific to the DNA of subjects suffering from the disorder from step e and the DNA obtained for diagnosis from step f to determine whether the patterns are the same or different and to diagnose thereby predisposition to the disorder if the patterns are the same.

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This invention provides a method for determining whether a substrate not known to be capable of binding to a mammalian betaine/GABA transporter can bind to the mammalian betaine/GABA transporter which comprises contacting a mammalian cell comprising an isolated DNA molecule encoding the betaine/GABA transporter with the substrate under conditions permitting binding of substrates known to bind to a transporter, detecting the presence of any of the substrate bound to the betaine/GABA transporter, and thereby determining whether the substrate binds to the betaine/GABA transporter.

This invention provides a method for determining whether a substrate not known to be capable of binding to a human betaine/GABA transporter can bind to a human betaine/GABA transporter which comprises contacting a mammalian cell comprising an isolated DNA molecule encoding the human betaine/GABA transporter with the substrate under conditions permitting binding of substrates known to bind to a transporter, detecting the presence of any of the substrate bound to the human betaine/GABA transporter.

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betaine/GABA transporter, and thereby determining whether the substrate binds to the human betaine/GABA transporter.

Brief Description of the Figures

Figures 1A - 1D. These four consecutive figures disclose the nucleotide sequence and deduced amino acid sequence of the human Betaine/GABA transporter. Nucleotides are presented in the 5' to 3' orientation and the coding region is numbered starting from the putative initiating methionine. DNA sequence was determined by the chain termination method of Sanger (1977) on denatured double-stranded plasmid templates using Sequenase. Deduced amino acid sequence (single letter abbreviation) by translation of a long open reading frame is shown.

Figures 2A-2G. Sequence alignment of human BGT-1 with other GABA transporters. Residues identical to hBGT-1 are shaded, and the 12 putative α -helical membrane-spanning domains (I-XII) are bracketed. BGT-1 is the dog betaine/GABA transporter (SEQ ID No. 8) (Yamauchi et al., 1992); mGAT-2 (SEQ ID No. 7) is the mouse homologue of rat GAT-2, originally referred to as GAT3 (Liu et al., 1991); rGAT-2 (SEQ ID No. 9) and rGAT-3 (SEQ ID No. 10) are rat GAT-2 and rat GAT-3, respectively (Borden et al., 1992).

Figure 3. GABA transport following transient and stable transfection of hS1a. Data show specific GABA uptake following transient (COS cells) and stable transfection (LM(tk⁺; clone 3) with human hS1a; control represents non-transfected cells. Transfections were performed as described in Methods. Cells were incubated for 10 minutes (37°C) with 50nM [³H]GABA, washed, and radioactivity determined. Data show specific uptake (mean \pm SD), expressed as cpm per mg cellular protein, and are from a representative experiment that was repeated many times with similar results.

Figure 4A. Northern blot analysis of hBGT-1 mRNA. Total RNA from human brain (25 μ g) was separated by agarose/formaldehyde gel electrophoresis, blotted, and hybridized with a 32 P-labeled fragment of the hBGT-1 cDNA. The autoradiogram was developed after 10 days and revealed a single approximately 3.1 Kb transcript.

Figure 4B. Northern blot analysis of hBGT-1 mRNA. A Northern blot containing poly A⁺ RNA (\approx 2 μ g) from various human brain regions was hybridized with 32 P-labeled hBGT-1 probe as described in Figure 4A, and developed after an overnight exposure. The blot was subsequently reprobed for β -actin (\approx 2.0 kb transcript, 20 minute exposure).

Figure 5A. Cellular Localization of mouse BGT-1 mRNA. Photomicrographs illustrating the localization of BGT mRNA in the mouse brain as revealed by *in situ* hybridization histochemistry. Low magnification reversal micrograph of a coronal section hybridized with the BGT antisense oligonucleotide, showing an intense hybridization signal over the septum (LS) and a moderate signal over anterior hypothalamus (AHA). Note that low levels of hybridization signal are present over most of the remainder of the section.

Figure 5B. Cellular Localization of mouse BGT-1 mRNA. Photomicrographs illustrating the localization of BGT mRNA in the mouse brain as revealed by *in situ* hybridization histochemistry. Low magnification reversal micrograph of a coronal section hybridized with the BGT sense probe. Only a weak signal is present over the lateral septum.

Figure 5C. High magnification photomicrograph of the hybridization signal over individual neurons in the

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lateral septum (mouse BGT-1 mRNA antisense probe). The cell nuclei at the left of the panel are clearly visible, with silver grains over the cytoplasm.

Figure 5D. Photomicrograph of the signal observed over individual cells in the anterior hypothalamus (mouse BGT-1 mRNA antisense probe). Marker bar = 20 μ m and applies to Figure 4C also.

Figure 6A. Morphology of neuronal cell cultures. Cultures were prepared as described in Methods. Neuronal cultures were stained with an anti-neurofilament antibody (Boehringer-Mannheim, Indianapolis, IN) and visualized with horseradish peroxidase.

Figure 6B. Morphology of Type 1 astrocyte cell culture. Cultures were prepared as described in Methods. Type 1 astrocyte cultures were stained with cresyl violet.

Figure 6C. Morphology of Type 0-2A/Type 2 astrocyte cell culture. Cultures were prepared as described in Methods. Type 0-2A/Type 2 astrocyte cultures were stained with cresyl violet.

Figure 7. NNC-711 inhibition of GABA transport in neuronal cultures. Neuronal cultures were incubated with [3 H]GABA and the indicated concentrations of NNC-711, as described in Methods. Data show specific uptake, expressed as percent of uptake in the absence of inhibitor. Data are from a single experiment that was repeated at least three times with similar results.

Figure 8. NNC-711 inhibition of GABA transport in O-2A/Type 2 astrocytic cultures. O-2A/Type 2 astrocytic cultures were incubated with [3 H]GABA and the indicated concentrations of NNC-711, as described in Methods.

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Data show specific uptake, expressed as percent of uptake in the absence of inhibitor. Data are the mean of three experiments:

Figure 9. NNC-711 inhibition of GABA transport in brain aggregates. Rat brain aggregates were incubated with [3 H]GABA and the indicated concentrations of NNC-711, as described in Methods. Data show specific uptake, expressed as percent of uptake in the absence of inhibitor. Data are from a single experiment that was repeated three times with similar results.

Figure 10. Localization of GABA transporter mRNAs. Northern blot analysis of GAT-1 (\approx 4.2 Kb), GAT-2 (\approx 2.4 Kb), GAT-3 (\approx 4.7 Kb), rBGAT-1 (\approx 2.4 Kb), and TAUT mRNA (\approx 6.2 Kb). Total RNA from neuronal (lane 1), Type 1 astrocyte (lane 2), and O-2A/Type 2 astrocyte (lane 3) cultures, was separated by formaldehyde/agarose gel electrophoresis, blotted, and hybridized at high stringency with 32 P-labeled transporter cDNAs (see Methods). The autoradiograms were developed after 5 days, with the exception of TAUT (overnight). Corresponding autoradiograms representing cyclophilin (1B15) hybridization are shown at right (45 minute exposure). Identical samples of neurons, Type 1 astrocytes, and O-2A/Type 2 astrocytes were used for each of five blots shown. Note that the levels of rBGAT-1 mRNA in astrocytes in the experiment shown are lower than average (see Table 8 for quantitation).

Figure 11. Amino acid relationships of cloned GABA transporters. The amino acid sequences of rat GAT-1 (Guastella et al., 1990), human GAT-1 (Nelson et al., 1990), rat GAT-2 (Borden et al., 1992), rat GAT-3 (Borden et al., 1992), human GAT-3 (Borden et al., submitted), and human BGT-1 (Borden et al., submitted) were compared using the Pileup program (Genetics

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Data are the mean of three experiments:

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Computer Group, Inc., Madison, USA). The lengths of the lines indicate the reciprocal of the sequence similarities.

Figure 12. Structure of lipophilic GABA transport inhibitors and their parent compounds.

Figure 13. Potency of Tiagabine at cloned GABA transporters. Cell lines expressing hGAT-1 (0), rGAT-2 (0), hGAT-3 (Δ) and rBGT-1 (◊) were incubated with [³H]GABA and the indicated concentrations of Tiagabine. Data show specific uptake, expressed as percent of uptake in the absence of inhibitor. Standard deviations, omitted for clarity, were $\leq 15\%$. This experiment was repeated with similar results.

Figure 14. Nucleotide Sequence and Deduced Amino Acid Sequence of the Rat Betaine/GABA Transporter. A DNA fragment representing rBGT-1 was amplified from rat brain cDNA using PCR and subcloned into pUC18. DNA sequence was determined by the chain termination method of Sanger (1977) on denatured double-stranded plasmid templates using Sequenase. Nucleotides are presented in the 5' to 3' orientation (SEQ ID No. 5); deduced amino acid sequence (single letter abbreviation) by translation of a long, open reading frame is shown (SEQ ID No. 6). The region of rBGT-1 encoded by the fragment corresponds to amino acids 84-139 of the human Betaine/GABA transporter.

Detailed Description of the Invention

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This invention provides an isolated nucleic acid molecule encoding a mammalian betaine/GABA transporter. As used herein, the term "isolated nucleic acid molecule" means a non-naturally occurring nucleic acid molecule that is, a molecule in a form which does not occur in nature. Examples of such an isolated nucleic acid molecule are an RNA, cDNA, or isolated genomic DNA molecule encoding a mammalian betaine/GABA transporter. As used herein, "betaine/GABA transporter" means a molecule which, under physiologic conditions, is substantially specific for the neurotransmitter GABA and betaine, is saturable and of high affinity for GABA and betaine. One embodiment of this invention is an isolated human nucleic acid molecule encoding a mammalian betaine/GABA transporter. Another embodiment of this invention is an isolated rat nucleic acid molecule encoding a mammalian betaine/GABA transporter. A preferred embodiment of this invention is an isolated nucleic acid molecule encoding a human betaine/GABA transporter. Such molecules may have coding sequences substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID No. 1) or Figure 14 (SEQ ID No. 5). The DNA molecule of Figures 1A - 1D (Sequence I.D. No. 1) encodes the sequence of a human betaine/GABA transporter gene. The DNA molecule of Figure 14 (SEQ ID No. 5) partially encodes a rat betaine/GABA transporter gene. One means of isolating a mammalian betaine/GABA transporter is to probe a mammalian genomic library with a natural or artificially designed DNA probe, using methods well known in the art. In the preferred embodiment of this invention, the mammalian betaine/GABA transporter is a human protein and the nucleic acid molecules encoding them are isolated from a human cDNA library or a human genomic DNA library. Degenerate oligonucleotide primers the sequences of

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which are derived from comparisons between conserved regions of several transporters are useful for identifying a nucleic acid molecule encoding a mammalian betaine/GABA transporter, obtaining a probe to a mammalian betaine/GABA transporter and for isolating a nucleic acid molecule encoding a mammalian betaine/GABA transporter. DNA and cDNA molecules which encode a human or mammalian betaine/GABA transporter are used to obtain complementary genomic DNA, cDNA or RNA from human, mammalian or other animal sources, or to isolate related cDNA or genomic clones by the screening of cDNA or genomic DNA libraries, by methods described in more detail below. Transcriptional regulatory elements from the 5' untranslated region of the isolated clone, and other stability, processing, transcription, translation, and tissue specificity determining regions from the 3' and 5' untranslated regions of the isolated gene are thereby obtained.

20 A sequence derived from the DNA encoding a human or a mammalian betaine/GABA transporter such as that derived from the sequence encoding the human betaine/GABA transporter in Figures 1A - 1D (SEQ ID NO. 1) can be used to identify and isolate human or a mammalian RNA or DNA encoding a betaine/GABA transporter subtype or a related transporter. Transporter subtypes may be products of the same gene or more than one gene. Products of the same gene are generated by alternative splicing of the RNA encoding the transporter, by rearrangements of the same gene encoding the transporter or by other means.

This invention provides an isolated nucleic acid molecule which has been so mutated as to be incapable of encoding a molecule having normal transporter activity, and not expressing native transporter. An example of a mutated nucleic acid molecule provided by

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this invention is an isolated nucleic acid molecule which has an in-frame stop codon inserted into the coding sequence such that the transcribed RNA is not translated into a protein having normal transporter activity.

This invention provides a cDNA molecule encoding a mammalian betaine/GABA transporter. This invention further provides a cDNA molecule encoding a human betaine/GABA transporter. The cDNA encoding the mammalian or human betaine/GABA transporter has coding sequence substantially the same as the coding sequence shown in Figures 1A - 1D. (Sequence I.D. No. 1). These molecules and their equivalents are obtained by the means described above.

This invention also provides an isolated protein which is a mammalian GABA transporter. One embodiment of this invention is a rat GABA transporter protein having the partial rat GABA transporter protein having an amino acid sequence substantially the same as the sequence shown in Figure 1A (Sequence I.D. No. 5) In a preferred embodiment of this invention, the protein is a human GABA transporter protein having an amino acid sequence substantially the same as the sequence shown in Figures 1A - 1D (Sequence I.D. Nos. 1 and 2). As used herein, the term "isolated protein" is intended to encompass a protein molecule free of other cellular components. One means for obtaining an isolated betaine/GABA transporter is to express DNA encoding the transporter in a suitable host, such as a bacterial (e.g. E. coli), yeast (e.g. S. cerevisiae), insect, or mammalian cell, using methods well known to those skilled in the art, and recovering the transporter protein after it has been expressed in such a host, again using methods well known in the art. The transporter may also be isolated from cells which

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express it, in particular from cells which have been transfected with the expression vectors described below in more detail.

This invention also provides a vector comprising an isolated nucleic acid molecule such as DNA, RNA, or cDNA, encoding a mammalian betaine/GABA transporter. This invention also provides a vector comprising an isolated nucleic acid molecule such as DNA, RNA, or cDNA, encoding a human betaine/GABA transporter.

Examples of vectors are viruses such as retroviruses, baculovirus, bacteriophages (such as phage lambda), cosmids, plasmids (such as PUC18, available from Pharmacia, Piscataway, NJ), and other recombination vectors. Nucleic acid molecules are inserted into vector genomes by methods well known to those skilled in the art. Examples of such plasmids are plasmids comprising cDNA having a coding sequence substantially the same as the coding sequence shown in Figures 1A - 1D (Seq. I.D. No. 1) and designated pCEXV-hBGT (ATCC Accession No. 75393). Another examples of such plasmids are plasmids comprising cDNA having a partial coding sequence substantially the same as the coding sequence shown in Figure 14 (Seq. I.D. No. 5) and designated PUC18-rBGT-1 (ATCC Accession No.). Alternatively, to obtain these vectors, insert and vector DNA can both be exposed to a restriction enzyme to create complementary ends on both molecules which base pair with each other and are then ligated together with a ligase. Alternatively, linkers can be ligated to the insert DNA which correspond to a restriction site in the vector DNA, which is then digested with the restriction enzyme which cuts at that site. Other means are also available.

This invention also provides expression vectors comprising a DNA molecule encoding a mammalian betaine/GABA transporter adapted for expression in a bacterial cell, a yeast cell, insect, or a mammalian bacterial cell, yeast, insect or mammalian cells operatively linked to the DNA encoding a mammalian betaine/GABA transporter or to the DNA encoding a human betaine/GABA transporter as to permit expression thereof. DNA having coding sequences substantially the same as the coding sequence shown in Figures 1A - 1D may usefully be inserted into the vectors to express mammalian or human betaine/GABA transporters. Regulatory elements required for expression include promoter sequences to bind RNA polymerase and transcription initiation sequences for ribosome binding. For example, a bacterial expression vector includes a promoter such as the lac promoter and for transcription initiation the Shine-Dalgarno sequence and the start codon AUG (Maniatis, et al., Molecular Cloning, Cold Spring Harbor Laboratory, 1982). Similarly, a eukaryotic expression vector includes a heterologous or homologous promoter for RNA polymerase II, a downstream polyadenylation signal, the start codon AUG, and a termination codon for detachment of the ribosome. Such vectors may be obtained commercially or assembled from the sequences described by methods well known in the art, for example the methods described above for constructing vectors in general. Expression vectors are useful to produce cells that express the transporter. Certain uses for such cells are described in more detail below.

In one embodiment of this invention a plasmid is adapted for expression in a bacterial, yeast, insect, or, in particular, a mammalian cell wherein the plasmid

comprises a DNA molecule encoding a mammalian betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the bacterial, yeast, insect, or mammalian cell operatively linked to the DNA encoding a mammalian betaine/ GABA transporter as to permit expression thereof. In another embodiment of this invention a plasmid is adapted for expression in a bacterial, yeast, insect, or, in particular, a mammalian cell wherein the plasmid comprises a DNA molecule encoding a human betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the bacterial, yeast, insect, or mammalian cell operatively linked to the DNA encoding a human betaine/GABA transporter to permit expression thereof. Suitable plasmids may include, but are not limited to plasmids adapted for expression in a mammalian cell, e.g., EYB or EYV. Examples of such plasmids adapted for expression in a mammalian cell are plasmids comprising cDNA having coding sequences substantially the same as the coding sequence shown in Figures 1A - 1D (SEQ ID NO. 1) and the regulatory elements necessary for expression of the DNA in the mammalian cell. A plasmid adapted for expression in a mammalian cell comprising the DNA encoding a human betaine/GABA transporter has been designated pcEXV-hBG7 and deposited under ATCC Accession No. 75393. A plasmid adapted for expression in a mammalian cell comprising the DNA partially encoding a rat betaine/GABA transporter has been designated pUC18-rBG7-1 and deposited under ATCC Accession No. Those skilled in the art will readily appreciate that numerous plasmids adapted for expression in a mammalian cell which comprise DNA encoding a mammalian or human betaine/GABA transporter and the regulatory elements necessary to express such DNA in the mammalian cell, may be constructed utilizing existing plasmids and adapted as appropriate to contain the regulatory elements

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necessary to express the DNA in the mammalian cell. The plasmids may be constructed by the methods described above for expression vectors and vectors in general, and by other methods well known in the art.

5 The deposits discussed supra were made pursuant to, and in satisfaction of, the provisions of the Budapest Treaty on the International Recognition of the Deposit of Microorganisms for the Purpose of Patent Procedure with the American Type Culture Collection (ATCC), 12301 Parklawn Drive, Rockville, Maryland 20852.

This invention provides a mammalian cell comprising a DNA molecule encoding a mammalian betaine/GABA transporter, such as a mammalian cell comprising a plasmid adapted for expression in a mammalian cell, which comprises a DNA molecule encoding a mammalian betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the mammalian cell operatively linked to the DNA encoding a mammalian transporter as to permit expression thereof. This invention also provides a mammalian cell comprising a DNA molecule encoding a human betaine/GABA transporter, such as a mammalian cell comprising a plasmid adapted for expression in a mammalian cell, which comprises a DNA molecule encoding a human betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the mammalian cell operatively linked to the DNA encoding a human transporter as to permit expression thereof. Numerous mammalian cells may be used as hosts, including, but not limited to, the mouse fibroblast cell NIH3T3; CHO cells, HeLa cells, Ltk cells, Cos cells, etc. Expression plasmids such as that described supra may be used to transfect mammalian cells by methods well known in the art such as calcium phosphate precipitation, or DNA encoding these transporters may be otherwise introduced into mammalian

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This invention provides a mammalian cell comprising a DNA molecule encoding a mammalian betaine/GABA transporter, such as a mammalian cell comprising a plasmid adapted for expression in a mammalian cell, which comprises a DNA molecule encoding a mammalian betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the mammalian cell operatively linked to the DNA encoding a mammalian transporter as to permit expression thereof. This invention also provides a mammalian cell comprising a DNA molecule encoding a human betaine/GABA transporter, such as a mammalian cell comprising a plasmid adapted for expression in a mammalian cell, which comprises a DNA molecule encoding a human betaine/GABA transporter and the regulatory elements necessary for expression of the DNA in the mammalian cell operatively linked to the DNA encoding a human transporter as to permit expression thereof. Numerous mammalian cells may be used as hosts, including, but not limited to, the mouse fibroblast cell NIH3T3; CHO cells, HeLa cells, Ltk cells, Cos cells, etc. Expression plasmids such as that described supra may be used to transfect mammalian cells by methods well known in the art such as calcium phosphate precipitation, or DNA encoding these transporters may be otherwise introduced into mammalian

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cells, e.g., by microinjection, to obtain mammalian cells which comprise DNA, e.g., cDNA or a plasmid, encoding a mammalian or a human betaine/GABA transporter.

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This invention provides a nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a unique sequence included within the sequence of a nucleic acid molecule encoding a mammalian betaine/GABA transporter. This invention also provides a nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a unique sequence included within the sequence of a nucleic acid molecule encoding a human betaine/GABA transporter, for example with a coding sequence included within the sequence shown in Figures 1A - 1D (SEQ ID NO. 1). As used herein, the phrase "specifically hybridizing" means the ability of a nucleic acid molecule to recognize a nucleic acid sequence complementary to its own and to form double-helical segments through hydrogen bonding between complementary base pairs. Nucleic acid probe technology is well known to those skilled in the art

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who will readily appreciate that such probes may vary greatly in length and may be labeled with a detectable label, such as a radioisotope or fluorescent dye, to facilitate detection of the probe. Detection of nucleic acid encoding a mammalian betaine/GABA transporter or human betaine/GABA transporter is useful as a diagnostic test for any disease process in which levels of expression of the corresponding betaine/GABA are altered. DNA probe molecules are produced by insertion of a DNA molecule which encodes the mammalian or human betaine/GABA transporter or fragments thereof into suitable vectors, such as plasmids or bacteriophages, followed by insertion into suitable

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bacterial host cells and replication and harvesting of the DNA probes, all using methods well known in the art. For example, the DNA may be extracted from a cell lysate using phenol and ethanol, digested with restriction enzymes corresponding to the insertion sites of the DNA into the vector (discussed above), electrophoresed, and cut out of the resulting gel. Examples of such DNA molecules are shown in Figures 1A - 1D (SEQ ID NO. 1). The probes are useful for 'in situ' hybridization or in order to locate tissues which express this gene family, or for other hybridization assays for the presence of these genes or their mRNA in various biological tissues. In addition, synthesized oligonucleotides (produced by a DNA synthesizer) complementary to the sequence of a DNA molecule which encodes a mammalian betaine/GABA transporter or complementary to the sequence of a DNA molecule which encodes a human betaine/GABA transporter, are useful as probes for these genes, for their associated mRNA, or for the isolation of related genes by homology screening of genomic or cDNA libraries, or by the use of amplification techniques such as the Polymerase Chain Reaction.

This invention also provides a method of detecting expression of a mammalian betaine/GABA transporter on the surface of a cell by detecting the presence of mRNA coding for the mammalian betaine/GABA transporter. This invention further provides a method of detecting the expression of a human betaine/GABA transporter on the surface of the cell by detecting the presence of mRNA coding for the corresponding betaine/GABA transporter. These methods comprise obtaining total mRNA from the cell using methods well known in the art and contacting the mRNA so obtained with a nucleic acid probe as described hereinabove, under hybridizing conditions, detecting the presence of mRNA hybridized

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who will readily appreciate that such probes may vary greatly in length and may be labeled with a detectable label, such as a radioisotope or fluorescent dye, to facilitate detection of the probe. Detection of nucleic acid encoding a mammalian betaine/GABA transporter or human betaine/GABA transporter is useful as a diagnostic test for any disease process in which levels of expression of the corresponding betaine/GABA are altered. DNA probe molecules are produced by insertion of a DNA molecule which encodes the mammalian or human betaine/GABA transporter or fragments thereof into suitable vectors, such as plasmids or bacteriophages, followed by insertion into suitable

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to the probe, and thereby detecting the expression of the transporter by the cell. Hybridization of probes to target nucleic acid molecules such as mRNA molecules employs techniques well known in the art. However, in one embodiment of this invention, nucleic acids are extracted by precipitation from lysed cells and the mRNA is isolated from the extract using a column which binds the poly-A tails of the mRNA molecules (Maniatis et al., 1982). The mRNA is then exposed to radiatively labelled probe on a nitrocellulose membrane, and the probe hybridizes to and thereby labels complementary mRNA sequences. Binding may be detected by autoradiography or scintillation counting. However, other methods for performing these steps are well known to those skilled in the art, and the discussion above is merely an example.

This invention provides an antisense oligonucleotide having a sequence capable of binding specifically with any sequences of an mRNA molecule which encodes a mammalian betaine/GABA transporter so as to prevent translation of the mammalian betaine/GABA transporter. This invention provides an antisense oligonucleotide having a sequence capable of binding specifically with any sequences of an mRNA molecule which encodes a human betaine/GABA transporter so as to prevent translation of the human betaine/GABA transporter. As used herein, the phrase "binding specifically" means the ability of an antisense oligonucleotide to recognize a nucleic acid sequence complementary to its own and to form double-helical segments through hydrogen bonding between complementary base pairs. The antisense oligonucleotide may have a sequence capable of binding specifically with any sequences of the cDNA molecules whose sequences are shown in Figures 1A - 1D (SEQ ID NO.: 1). A particular example of an antisense

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oligonucleotide is an antisense oligonucleotide comprising chemical analogues of nucleotides.

This invention also provides a pharmaceutical composition comprising an effective amount of the oligonucleotide described above effective to reduce expression of a mammalian betaine/GABA transporter by passing through a cell membrane and binding specifically with mRNA encoding a mammalian betaine/GABA transporter in the cell so as to prevent its translation and a pharmaceutically acceptable hydrophobic carrier capable of passing through a cell membrane. This invention also provides a pharmaceutical composition comprising an effective amount of the oligonucleotide described above effective to reduce expression of a human betaine/GABA transporter by passing through a cell membrane and binding specifically with mRNA encoding a human betaine/GABA transporter in the cell so as to prevent its translation and a pharmaceutically acceptable hydrophobic carrier capable of passing through a cell membrane. As used herein, the term "pharmaceutically acceptable carrier" encompasses any of the standard pharmaceutical carriers, such as a phosphate buffered saline solution, water, and emulsions, such as an oil/water or water/oil emulsion, and various types of wetting agents. The oligonucleotide may be coupled to a substance which inactivates mRNA, such as a ribozyme. The pharmaceutically acceptable hydrophobic carrier capable of passing through cell membranes may also comprise a structure which binds to a transporter specific for a selected cell type and is thereby taken up by cells of the selected cell type. The structure may be part of a protein known to bind a cell-type specific transporter, for example an insulin molecule, which would target pancreatic cells. DNA molecules having coding sequences substantially the same as the

coding sequence shown in Figures 1A - 1D (SEQ ID NO. 1) may be used as the oligonucleotides of the pharmaceutical composition.

This invention also provides a method of treating abnormalities which are alleviated by reduction of expression of a betaine/GABA transporter. This method comprises administering to a subject an effective amount of the pharmaceutical composition described above effective to reduce expression of the betaine/GABA transporter by the subject. This invention further provides a method of treating an abnormal condition related to betaine/GABA transporter activity which comprises administering to a subject an amount of the pharmaceutical composition described above effective to reduce expression of the betaine/GABA transporter by the subject. Examples of such abnormal conditions are epilepsy, migraine, ischemia, myoclonus, spasticity, and chronic pain.

Antisense oligonucleotide drugs inhibit translation of mRNA encoding these transporters. Synthetic antisense oligonucleotides, or other antisense chemical structures are designed to bind to mRNA encoding a betaine/GABA transporter and are useful as drugs to inhibit expression of betaine/GABA transporter genes in patients. This invention provides a means to therapeutically alter levels of expression of a mammalian betaine/GABA transporters by the use of a synthetic antisense oligonucleotide drug (SAOD) which inhibits translation of mRNA encoding these transporters. Synthetic antisense oligonucleotides, or other antisense chemical structures designed to recognize and selectively bind to mRNA, are constructed to be complementary to portions of the nucleotide sequence shown in Figures 1A - 1D (SEQ ID NO. 1) of DNA, RNA or of chemically modified, artificial nucleic acids.

The SAOD is designed to be stable in the blood stream for administration to patients by injection, or in laboratory cell culture conditions, for administration to cells removed from the patient. The SAOD is designed to be capable of passing through cell membranes in order to enter the cytoplasm of the cell by virtue of physical and chemical properties of the SAOD which render it capable of passing through cell membranes (e.g., by designing small, hydrophobic SAOD chemical structures) or by virtue of specific transport systems in the cell which recognize and transport the SAOD into the cell. In addition, the SAOD can be designed for administration only to certain selected cell populations by targeting the SAOD to be recognized by specific cellular uptake mechanisms which bind and take up the SAOD only within certain selected cell populations. For example, the SAOD may be designed to bind to a transporter found only in a certain cell type, as discussed above. The SAOD is also designed to recognize and selectively bind to the target mRNA sequence, which may correspond to a sequence contained within the sequence shown in Figures 1A - 1D (SEQ ID NO. 1) by virtue of complementary base pairing to the mRNA. Finally, the SAOD is designed to inactivate the target mRNA sequence by any of three mechanisms: 1) by binding to the target mRNA and thus inducing degradation of the mRNA by intrinsic cellular mechanisms such as RNASE I digestion, 2) by inhibiting translation of the mRNA target by interfering with the binding of translation-regulating factors or of ribosomes, or 3) by inclusion of other chemical structures, such as ribozyme sequences or reactive chemical groups, which either degrade or chemically modify the target mRNA. Synthetic antisense oligonucleotide drugs have been shown to be capable of the properties described above when directed against mRNA targets (Cohen, T.S., 1989; Weintraub, H.M.,

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1990). In addition, coupling of ribozymes to antisense oligonucleotides is a promising strategy for inactivating target mRNA (N. Sarker et al. 1990). An SAOD serves as an effective therapeutic agent if it is designed to be administered to a patient by injection, or if the patient's target cells are removed, treated with the SAOD in the laboratory, and replaced in the patient. In this manner, an SAOD serves as a therapy to reduce transporter expression in particular target cells of a patient, in any clinical condition which may benefit from reduced expression of GABA or taurine transporters.

This invention provides an antibody directed to the mammalian betaine/GABA transporter. This antibody may comprise, for example, a monoclonal antibody directed to an epitope of a mammalian betaine/GABA transporter present on the surface of a cell, the epitope having an amino acid sequence substantially the same as the amino acid sequence for a cell surface epitope of the human betaine/GABA transporter included in the amino acid sequence shown in Figures 1A - 1D (SEQ ID NOS. 1 and 3). This invention provides an antibody directed to a human betaine/GABA transporter. This antibody may comprise, for example, a monoclonal antibody directed to an epitope of a human betaine/GABA transporter present on the surface of a cell, the epitope having an amino acid sequence substantially the same as an amino acid sequence for a cell surface epitope of the human betaine/GABA transporter included in the amino acid sequence shown in Figures 1A - 1D (SEQ ID NOS. 1 and 3).

Amino acid sequences may be analyzed by methods well known to those skilled in the art to determine whether they produce hydrophobic or hydrophilic regions in the proteins which they build. In the case of cell membrane proteins, hydrophobic regions are well known to form the part of the protein that is inserted into

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the lipid bilayer which forms the cell membrane, while hydrophilic regions are located on the cell surface, in an aqueous environment. Therefore, antibodies directed to hydrophilic amino acid sequences specific to a human transporter will bind to a surface epitope of a human taurine transporter and antibodies directed to the conserved hydrophilic amino acid sequences shown in Figures 1A - 1D (SEQ ID NOS. 1 and 3) will bind to a surface epitope of a mammalian betaine/GABA transporter. Antibodies directed to mammalian or human transporters may be serum-derived or monoclonal and are prepared using methods well known in the art. For example, monoclonal antibodies are prepared using hybridoma technology by fusing antibody producing B cells from immunized animals with myeloma cells and selecting the resulting hybridoma cell line producing the desired antibody. Cells such as NIH3T3 cells or Ltk⁻ cells may be used as immunogens to raise such an antibody. Alternatively, synthetic peptides may be prepared using commercially available machines and the amino acid sequences shown in Figures 1A - 1D (SEQ ID NOS. 1 and 2). As a still further alternative, DNA, such as a cDNA or a fragment thereof, may be cloned and expressed and the resulting polypeptide recovered and used as an immunogen. These antibodies are useful to detect the presence of mammalian transporters encoded by the isolated DNA, or to inhibit the function of the transporters in living animals, in humans, or in biological tissues or fluids isolated from animals or humans.

This invention also provides a pharmaceutical composition which comprises an effective amount of an antibody directed to an epitope of the mammalian transporter, effective to block binding of naturally occurring substrates to the transporter, and a pharmaceutically acceptable carrier. A monoclonal

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membrane proteins, hydrophobic regions are well known to form the part of the protein that is inserted into

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antibody directed to a conserved epitope of a human betaine/GABA transporter present on the surface of a cell which has an amino acid sequence substantially the same as an amino acid sequence for a cell surface epitope of the human betaine/GABA transporter included in the amino acid sequences shown in Figures 1A - 1D (SEQ ID Nos. 1 and 3) is useful for this purpose.

This invention also provides a pharmaceutical composition which comprises an effective amount of an antibody directed to an epitope of the human betaine/GABA transporter, effective to block binding of naturally occurring substrates to the human betaine/GABA transporter, and a pharmaceutically acceptable carrier. A monoclonal antibody directed to an epitope of a human betaine/GABA transporter present on the surface of a cell which has an amino acid sequence substantially the same as an amino acid sequence for a cell surface epitope of the human betaine/GABA transporter included in the amino acid sequences shown in Figures 1A - 1D (SEQ ID Nos. 1 and 3) is useful for this purpose.

This invention also provides a method of treating abnormalities in a subject which are alleviated by reduction of expression of a mammalian betaine/GABA transporter which comprises administering to the subject an effective amount of the pharmaceutical composition described above effective to block binding of naturally occurring substrates to the mammalian betaine/GABA transporter and thereby alleviate abnormalities resulting from overexpression of the mammalian betaine/GABA transporter. This invention also provides a pharmaceutical composition which comprises an effective amount of an antibody directed to an epitope of a human betaine/GABA transporter, effective to block binding of naturally occurring

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substrates to the human betaine/GABA transporter, and a pharmaceutically acceptable carrier. A monoclonal antibody directed to a conserved epitope specific to a betaine/GABA transporter present on the surface of a cell which has an amino acid sequence substantially the same as an amino acid sequence for a cell surface epitope of the human betaine/GABA transporter included in the amino acid sequence shown in Figures 1A - 1D (SEQ ID Nos. 1 and 3) is useful for this purpose.

Binding of the antibody to the transporter prevents the transporter from functioning, thereby neutralizing the effects of overexpression. The monoclonal antibodies described above are both useful for this purpose. This invention additionally provides a method of treating an abnormal condition related to an excess of transporter activity which comprises administering to a subject an amount of the pharmaceutical composition described above effective to block binding of naturally occurring substrates to the transporter and thereby alleviate the abnormal condition. Some examples of abnormal conditions associated with abnormal betaine/GABA transporter activity are epilepsy, migraine, ischemia, myoclonus, spasticity, and the treatment of chronic pain.

This invention provides methods of detecting the presence of a betaine/GABA transporter on the surface of a cell which comprises contacting the cell with an antibody directed to the mammalian betaine/GABA transporter or an antibody directed to the human betaine/GABA transporter, under conditions permitting binding of the antibody to the transporter, detecting the presence of the antibody bound to the cell, and thereby the presence of the mammalian betaine/GABA transporter or the human betaine/GABA transporter on the surface of the cell. Such methods are useful for determining whether a given cell is defective in

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expression of betaine/GABA transporter on the surface of the cell. Bound antibodies are detected by methods well known in the art, for example by binding fluorescent markers to the antibodies and examining the cell sample under a fluorescence microscope to detect fluorescence on a cell indicative of antibody binding. The monoclonal antibodies described above are useful for this purpose.

This invention provides a transgenic nonhuman mammal expressing DNA encoding a mammalian betaine/GABA transporter. This invention further provides a transgenic nonhuman mammal expressing DNA encoding a human betaine/GABA transporter. This invention also provides a transgenic nonhuman mammal expressing DNA encoding a mammalian betaine/GABA transporter so mutated as to be incapable of normal transporter activity and not expressing native betaine/GABA transporter activity. This invention further provides a transgenic nonhuman mammal expressing DNA encoding a human betaine/GABA transporter so mutated as to be incapable of normal transporter activity, and not expressing native betaine/GABA transporter.

This invention provides a transgenic nonhuman mammal whose genome comprises DNA encoding a mammalian betaine/GABA transporter so placed as to be transcribed into antisense mRNA which is complementary to mRNA encoding the betaine/GABA transporter and which hybridizes to mRNA encoding the betaine/GABA transporter thereby reducing its translation. This invention further provides a transgenic nonhuman mammal whose genome comprises DNA encoding a human betaine/GABA transporter so placed as to be transcribed into antisense mRNA which is complementary to mRNA encoding a betaine/GABA transporter and which hybridizes to mRNA encoding a betaine/GABA transporter.

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thereby reducing its translation. The DNA may additionally comprise an inducible promoter or additionally comprise tissue specific regulatory elements, so that expression can be induced, or restricted to specific cell types. Examples of DNA are 5 DNA or cDNA molecules having a coding sequence substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID Nos. 1). An example of a transgenic animal is a transgenic mouse. Examples of tissue specificity-determining regions are the metallothionein promoter (Low et al., 1986,) and the L7 promoter (Oberdick et al. 1990).

Animal model systems which elucidate the physiological and behavioral roles of mammalian transporters are produced by creating transgenic animals in which the expression of a transporter is either increased or decreased, or the amino acid sequence of the expressed transporter protein is altered, by a variety of techniques. Examples of these techniques include, but are not limited to: 1) Insertion of normal or mutant versions of DNA encoding a mammalian transporter or homologous animal versions of these genes, by microinjection, retroviral infection or other means well known to those skilled in the art, into appropriate fertilized embryos in order to produce a transgenic animal (Hogan et al., 1986) Homologous recombination (Cappechi, M.R., 1989; Zimmer A., and Gruss, P., 1989) of mutant or normal, human or animal 10 versions of these genes with the native gene locus in transgenic animals to alter the regulation of expression or the structure of these transporters. The technique of homologous recombination is well known in the art. It replaces the native gene with the inserted gene and so is useful for producing an animal that cannot express native transporter but does express, for example, an inserted mutant transporter, which has

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replaced the native transporter in the animal's genome by recombination, resulting in underexpression of the transporter. Microinjection adds genes to the genome, but does not remove them, and so is useful for producing an animal which expresses its own and added transporters, resulting in overexpression of the transporter.

One means available for producing a transgenic animal, with a mouse as an example, is as follows: Female mice are mated, and the resulting fertilized eggs are dissected out of their oviducts. The eggs are stored in an appropriate medium such as M2 medium (Hogan et al. 1986). DNA or cDNA encoding a human betaine/GABA transporter is purified from a vector (such as plasmid pcEXV-hBGT, ATCC Accession No. 75393, described above) by methods well known in the art. Inducible promoters may be fused with the coding region of the DNA to provide an experimental means to regulate expression of the trans-gene. Alternatively or in addition, tissue specific regulatory elements may be fused with the coding region to permit tissue-specific expression of the trans-gene. The DNA, in an appropriately buffered solution, is put into a microinjection needle (which may be made from capillary tubing using a pipet puller) and the egg to be injected is put in a depression slide. The needle is inserted into the pronucleus of the egg, and the DNA solution is injected. The injected egg is then transferred into the oviduct of a pseudopregnant mouse (a mouse stimulated by the appropriate hormones to maintain pregnancy but which is not actually pregnant), where it proceeds to the uterus, implants, and develops to term. As noted above, microinjection is not the only method for inserting DNA into the egg cell, and is used here only for exemplary purposes.

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Since the normal action of transporter-specific drugs is to activate or to inhibit the transporter, the transgenic animal model systems described above are useful for testing the biological activity of drugs directed against these transporters even before such drugs become available. These animal model systems are useful for predicting or evaluating possible therapeutic applications of drugs which activate or inhibit these transporters by inducing or inhibiting expression of the native or trans-gene and thus increasing or decreasing expression of normal or mutant transporters in the living animal. Thus, a model system is produced in which the biological activity of drugs directed against these transporters are evaluated before such drugs become available. The transgenic animals which over or under produce the transporter indicate by their physiological state whether over or under production of the transporter is therapeutically useful. It is therefore useful to evaluate drug action based on the transgenic model system. One use is based on the fact that it is well known in the art that a drug such as an antidepressant acts by blocking neurotransmitter uptake, and thereby increases the amount of neurotransmitter in the synaptic cleft. The physiological result of this action is to stimulate the production of less transporter by the affected cells, leading eventually to underexpression. Therefore, an animal which underexpresses transporter is useful as a test system to investigate whether the actions of such drugs which result in under expression are in fact therapeutic. Another use is that if overexpression is found to lead to abnormalities, then a drug which down-regulates or acts as an antagonist to the transporter is indicated as worth developing, and if a promising therapeutic application is uncovered by these animal model systems, activation or inhibition of the GABA transporter is achieved therapeutically either by

producing agonist or antagonist drugs directed against these GABA transporters or by any method which increases or decreases the expression of these transporters in man.

5 Further provided by this invention is a method of determining the physiological effects of expressing varying levels of a mammalian betaine/GABA transporter which comprises producing a transgenic nonhuman animal whose levels of mammalian betaine/GABA transporter expression are varied by use of an inducible promoter which regulates transporter expression. This invention also provides a method of determining the physiological effects of expressing varying levels of mammalian Betaine/GABA transporter which comprises producing a panel of transgenic nonhuman animals each expressing a different amount of the mammalian betaine/GABA transporter. Such animals may be produced by introducing different amounts of DNA encoding a mammalian betaine/GABA transporter into the oocytes from which the transgenic animals are developed.

This invention provides a method of determining the physiological effects of expressing varying levels of a human betaine/GABA transporter which comprises producing a transgenic nonhuman animal whose levels of human betaine/GABA transporter expression are varied by use of an inducible promoter which regulates transporter expression. This invention also provides a method of determining the physiological effects of expressing varying levels of a human betaine/GABA transporter which comprises producing a panel of transgenic nonhuman animals each expressing a different amount of the human betaine/GABA transporter. Such animals may be produced by introducing different amounts of DNA encoding a human betaine/GABA

transporter into the oocytes from which the transgenic animals are developed.

This invention also provides a method for identifying 5 a substance capable of alleviating abnormalities resulting from overexpression of a mammalian betaine/GABA transporter comprising administering the substance to a transgenic nonhuman mammal expressing at least one artificially introduced DNA molecule encoding a mammalian betaine/GABA transporter and determining whether the substance alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of overexpression of the nonhuman mammal betaine/GABA transporter. This invention also provides a method for identifying a substance capable of alleviating abnormalities resulting from overexpression of a human transporter comprising administering the substance to a transgenic nonhuman mammal expressing at least one artificially introduced DNA molecule encoding a human betaine/GABA transporter and determining whether the substance alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of overexpression of a human betaine/GABA transporter. As used herein, the term "substance" means a compound or composition which may be natural, synthetic, or a product derived from screening. Examples of DNA molecules are DNA or cDNA molecules having a coding sequence substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID NO: 1).

This invention provides a pharmaceutical composition comprising an amount of the substance described *supra* effective to alleviate the abnormalities resulting from overexpression of a mammalian betaine/GABA transporter and a pharmaceutically acceptable carrier. This invention also provides a pharmaceutical composition

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comprising an amount of the substance described above effective to alleviate the abnormalities resulting from overexpression of a human betaine/GABA transporter and a pharmaceutically acceptable carrier.

- 5 This invention also provides a method for treating the abnormalities resulting from overexpression of a mammalian betaine/GABA transporter which comprises administering to a subject an amount of the pharmaceutical composition described above effective to alleviate the abnormalities resulting from overexpression of a mammalian betaine/GABA transporter. This invention further provides a method for treating the abnormalities resulting from overexpression of a human betaine/GABA transporter which comprises administering to a subject an amount of the pharmaceutical composition described above effective to alleviate the abnormalities resulting from overexpression of the human betaine/GABA transporter.
- 10 This invention provides a method for identifying a substance capable of alleviating the abnormalities resulting from underexpression of a mammalian betaine/GABA transporter comprising administering the substance to the transgenic nonhuman mammal described above which expresses only nonfunctional mammalian transporter and determining whether the substance alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of underexpression of a mammalian betaine/GABA transporter. This invention further provides a method for identifying a substance capable of alleviating the abnormalities resulting from underexpression of a human betaine/GABA transporter comprising administering the substance to the transgenic nonhuman mammal described above which expresses only nonfunctional human betaine/GABA and determining whether the substance
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alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of underexpression of a human betaine/GABA.

- 5 This invention also provides a pharmaceutical composition comprising an amount of a substance effective to alleviate abnormalities resulting from underexpression of a mammalian betaine/GABA transporter and a pharmaceutically acceptable carrier. This invention also provides a pharmaceutical composition comprising an amount of a substance effective to alleviate abnormalities resulting from underexpression of a human betaine/GABA and a pharmaceutically acceptable carrier.
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- This invention provides a method for treating the abnormalities resulting from underexpression of a mammalian betaine/GABA transporter which comprises administering to a subject an amount of the pharmaceutical composition described above effective to alleviate the abnormalities resulting from underexpression of a mammalian betaine/GABA transporter which comprises administering to a subject an amount of the pharmaceutical composition described above effective to alleviate the abnormalities resulting from underexpression of a mammalian betaine/GABA transporter. This invention further provides a method for treating the abnormalities resulting from underexpression of a human betaine/GABA transporter which comprises administering to a subject an amount of the pharmaceutical composition described above effective to alleviate the abnormalities resulting from underexpression of a human betaine/GABA transporter.
- This invention provides a method for diagnosing a predisposition to a disorder associated with the expression of a specific mammalian betaine/transporter allele which comprises: a) obtaining DNA of subjects suffering from the disorder; b) performing a restriction digest of the DNA with a panel of restriction enzymes; c) electrophoretically separating

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the resulting DNA fragments on a sizing gel; d) contacting the resulting gel with a nucleic acid probe capable of specifically hybridizing to DNA encoding a mammalian betaine/GABA transporter and labelled with a detectable marker; e) detecting labelled bands which have hybridized to the DNA encoding a mammalian betaine/GABA transporter labelled with a detectable marker to create a unique band pattern specific to the DNA of subjects suffering from the disorder; f) preparing DNA obtained for diagnosis by steps a-e; and g) comparing the unique band pattern specific to the DNA of subjects suffering from the disorder from step e and the DNA obtained for diagnosis from step f to determine whether the patterns are the same or different and thereby to diagnose predisposition to the disorder if the patterns are the same. This method may also be used to diagnose a disorder associated with the expression of a specific mammalian betaine/GABA transporter allele.

This invention provides a method for diagnosing a predisposition to a disorder associated with the expression of a specific human betaine/GABA transporter allele which comprises: a) obtaining DNA of subjects suffering from the disorder; b) performing a restriction digest of the DNA with a panel of restriction enzymes; c) electrophoretically separating the resulting DNA fragments on a sizing gel; d) contacting the resulting gel with a nucleic acid probe capable of specifically hybridizing to DNA encoding a human betaine/GABA transporter and labelled with a detectable marker; e) detecting labelled bands which have hybridized to the DNA encoding a human betaine/GABA labelled with a detectable marker to create a unique band pattern specific to the DNA of subjects suffering from the disorder; f) preparing DNA obtained for diagnosis by steps a-e; and g) comparing

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the unique band pattern specific to the DNA of subjects suffering from the disorder from step e and the DNA obtained for diagnosis from step f to determine whether the patterns are the same or different and thereby to diagnose predisposition to the disorder if the patterns are the same. This method may also be used to diagnose a disorder associated with the expression of a specific human betaine/GABA transporter allele.

This invention provides a method of preparing an isolated betaine/GABA transporter which comprises inducing cells to express transporter, recovering the transporter from the resulting cells, and purifying the transporter so recovered. An example of an isolated betaine/GABA transporter is an isolated protein having substantially the same amino acid sequence as the amino acid sequence shown in Figures 1A - 1D (SEQ ID NO. 1). This invention further provides a method for preparing an isolated human GABA transporter which comprises inducing cells to express the human betaine/GABA transporter, recovering the human betaine/GABA transporter from the resulting cells, and purifying the human betaine/GABA transporter so recovered. An example of an isolated human betaine/GABA transporter is an isolated protein having substantially the same amino acid sequence as the amino acid sequence shown in Figures 1A - 1D (SEQ ID NOS. 1 and 3). For example, cells can be induced to express transporters by exposure to substances such as hormones. The cells can then be homogenized and the betaine/GABA transporter isolated from the homogenate using an affinity column comprising, for example, GABA, betaine or another substance which is known to bind to the betaine/GABA transporter. The resulting fractions can then be purified by contacting them with an ion exchange column, and determining which fraction contains

betaine/GABA transporter activity or binds anti-betaine/GABA transporter antibodies.

This invention provides a method of preparing the isolated mammalian betaine/GABA transporter which comprises inserting nucleic acid encoding the mammalian betaine/GABA transporter in a suitable vector, inserting the resulting vector in a suitable host cell, recovering the transporter produced by the resulting cell, and purifying the transporter so recovered. An example of an isolated betaine/GABA transporter is an isolated protein having substantially the same amino acid sequence as the amino acid sequence shown in Figures 1A - 1D (SEQ ID NOS 1 and 3). This invention also provides a method of preparing the isolated human betaine/GABA transporter which comprises inserting nucleic acid encoding a human betaine/GABA transporter in a suitable vector, inserting the resulting vector in a suitable host cell, recovering the transporter produced by the resulting cell, and purifying the transporter so recovered. These methods for preparing mammalian or human betaine/GABA transporter uses recombinant DNA technology methods well known in the art. For example, isolated nucleic acid encoding a mammalian or human betaine/GABA transporter is inserted in a suitable vector, such as an expression vector. A suitable host cell, such as a bacterial cell, or a eukaryotic cell such as a yeast cell, is transfected with the vector. Betaine/GABA transporter is isolated from the culture medium by affinity purification or by chromatography or by other methods well known in the art.

This invention provides a method for determining whether a compound not known to be capable of binding to a mammalian betaine/GABA transporter can bind to the mammalian betaine/GABA transporter which comprises

contacting a mammalian cell comprising a DNA molecule encoding a mammalian betaine/GABA transporter with the compound under conditions permitting binding of compounds known to bind to the transporter, detecting the presence of any of the compound bound to the betaine/GABA transporter, and thereby determining whether the substrate binds to the betaine/GABA transporter.

This invention provides a method for determining whether a compound not known to be capable of binding to a human betaine/GABA transporter can bind to the human betaine/GABA transporter which comprises contacting a mammalian cell comprising a DNA molecule encoding a human betaine/GABA transporter with the compound under conditions permitting binding of compounds known to bind to the transporter, detecting the presence of any of the compound bound to the betaine/GABA transporter, and thereby determining whether the substrate binds to the betaine/GABA transporter. The DNA in the cell may have a coding sequence substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID NO. 1). Preferably, the mammalian cell is nonneuronal in origin. An example of a nonneuronal mammalian cell is a Cos7 cell or an Ltk- cell. The preferred method for determining whether a compound is capable of binding to a mammalian or a human betaine/GABA transporter comprises contacting a transfected nonneuronal mammalian cell (i.e. a cell that does not naturally express any type of transporter, thus will only express such a transporter if it is transfected into the cell) expressing a transporter on its surface, or contacting a membrane preparation derived from such a transfected cell, with the substrate under conditions which are known to prevail, and thus to be associated with, in vivo binding of the substrates to a transporter,

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detecting the presence of any of the substrate being tested bound to the transporter, on the surface of the cell, and thereby determining whether the substrate binds to the transporter. This response system is obtained by transfection of isolated DNA into a suitable host cell. Such a host system might be isolated from pre-existing cell lines, or can be generated by inserting appropriate components into existing cell lines. Such a transfection system provides a complete response system for investigation or assay of the functional activity of mammalian transporters with substrates as described above. Transfection systems are useful as living cell cultures for competitive binding assays between known or candidate drugs and substrates which bind to the transporter and which are labeled by radioactive, spectroscopic or other reagents. Membrane preparations containing the transporter isolated from transfected cells are also useful for these competitive binding assays. A transfection system constitutes a "drug discovery system" useful for the identification of natural or synthetic compounds with potential for drug development that can be further modified or used directly as therapeutic compounds to activate or inhibit the natural functions of the mammalian transporter and/or the human transporter. The transfection system is also useful for determining the affinity and efficacy of known drugs at the mammalian transporter sites and human transporter sites.

This invention also provides a method of screening drugs to identify drugs which specifically interact with, and bind to, the mammalian betaine/GABA transporter on the surface of a cell which comprises contacting a mammalian cell comprising a DNA molecule encoding a mammalian betaine/GABA transporter on the surface of a cell with a plurality of drugs, detecting those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, the mammalian betaine/GABA transporter. This invention also provides a method of screening drugs to identify drugs which specifically interact with, and bind to, a human betaine/GABA transporter on the surface of a cell which comprises contacting a mammalian cell comprising a DNA molecule encoding a human betaine/GABA transporter on the surface of a cell with a plurality of drugs, detecting those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, the human betaine/GABA transporter. The DNA in the cell may have a coding sequence substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID NO. 1). Various methods of detection may be employed. The drugs may be "labeled" by association with a detectable marker substance (e.g., radiolabel or a non-isotopic label such as biotin). Preferably, the mammalian cell is nonneuronal in origin. An example of a nonneuronal mammalian cell is a COS7 cell or an L tk- cell. Drug candidates are identified by choosing chemical compounds which bind with high affinity to the expressed transporter protein in transfected cells, using radioligand binding methods well known in the art, examples of which are shown in the binding assays described herein. Drug candidates are also screened for selectivity by identifying compounds which bind with high affinity to one particular transporter subtype but do not bind with high affinity to any other transporter subtype, or to any other known transporter site. Because selective, high affinity compounds interact primarily with the target transporter site after administration to the patient, the chances of producing a drug with unwanted side effects are minimized by this approach. This invention provides a pharmaceutical composition

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those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, the mammalian betaine/GABA transporter. This invention also provides a method of screening drugs to identify drugs which specifically interact with, and bind to, a human betaine/GABA transporter on the surface of a cell which comprises contacting a mammalian cell comprising a DNA molecule encoding a human betaine/GABA transporter on the surface of a cell with a plurality of drugs, detecting those drugs which bind to the mammalian cell, and thereby identifying drugs which specifically interact with, and bind to, the human betaine/GABA transporter. The DNA in the cell may have a coding sequence substantially the same as the coding sequences shown in Figures 1A - 1D (SEQ ID NO. 1). Various methods of detection may be employed. The drugs may be "labeled" by association with a detectable marker substance (e.g., radiolabel or a non-isotopic label such as biotin). Preferably, the mammalian cell is nonneuronal in origin. An example of a nonneuronal mammalian cell is a COS7 cell or an L tk- cell. Drug candidates are identified by choosing chemical compounds which bind with high affinity to the expressed transporter protein in transfected cells, using radioligand binding methods well known in the art, examples of which are shown in the binding assays described herein. Drug candidates are also screened for selectivity by identifying compounds which bind with high affinity to one particular transporter subtype but do not bind with high affinity to any other transporter site. Because selective, high affinity compounds interact primarily with the target transporter site after administration to the patient, the chances of producing a drug with unwanted side effects are minimized by this approach. This invention provides a pharmaceutical composition

comprising a drug identified by the method described above and a pharmaceutically acceptable carrier. As used herein, the term "pharmaceutically acceptable carrier" encompasses any of the standard pharmaceutical carriers, such as a phosphate buffered saline solution, emulsions, such as an oil/water or water/oil emulsion, and various types of wetting agents. Once the candidate drug has been shown to be adequately bioavailable following a particular route of administration, for example orally or by injection (adequate therapeutic concentrations must be maintained at the site of action for an adequate period to gain the desired therapeutic benefit), and has been shown to be non-toxic and therapeutically effective in appropriate disease models, the drug may be administered to patients by that route of administration determined to make the drug bioavailable, in an appropriate solid or solution formulation, to gain the desired therapeutic benefit.

Applicants have identified a human betaine/GABA transporter and have described methods for the identification of pharmacological compounds for therapeutic treatments. Pharmacological compounds which are directed against specific transporter subtypes provide effective new therapies with minimal side effects.

Elucidation of the molecular structures of the betaine/GABA transporter is an important step in the understanding of GABAergic neurotransmission. This disclosure reports the isolation; amino acid sequence, and functional expression of a DNA clone from human brain which encodes a betaine/GABA transporter. The identification of this betaine/GABA transporter will play a pivotal role in elucidating the molecular mechanisms underlying GABAergic transmission, and should also aid in the development of novel therapeutic agents.

Complementary DNA clones (designated hS1a, hS13a, hS26a and hS38a) encoding betaine/GABA transporters have been isolated from human brain, and their functional properties have been examined in mammalian cells. The nucleotide sequence of hS1a predicts a protein of 614 amino acids with 12 highly hydrophobic regions compatible with membrane-spanning domains. When incubated with 50 nM [³H]GABA, COS cells transiently transfected with hS1a accumulated approximately 10-fold greater radioactivity as non-transfected control cells. In stable LM tk- cell lines expressing hS1a, a 92 fold enhancement of [³H]GABA uptake was observed, compared to non-transfected cells.

Analysis of the betaine/GABA transporter structure and function provides a model for the development of drugs useful for the treatment of epilepsy, migraine, ischemia, myoclonus, spasticity, and chronic pain.

This invention identifies for the first time a betaine/GABA transporter protein, its amino acid sequence, and its human gene. The information and experimental tools provided by this discovery are useful to generate new therapeutic agents, and new therapeutic or diagnostic assays for this new transporter protein, its associated mRNA molecules or its associated genomic DNAs. The information and experimental tools provided by this discovery will be useful to generate new therapeutic agents, and new therapeutic or diagnostic assays for this new transporter protein, its associated mRNA molecules, or its associated genomic DNAs.

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This invention identifies for the first time a betaine/GABA transporter protein, its amino acid sequence, and its human gene. The information and experimental tools provided by this discovery are useful to generate new therapeutic agents, and new therapeutic or diagnostic assays for this new transporter protein, its associated mRNA molecules or its associated genomic DNAs. The information and experimental tools provided by this discovery will be useful to generate new therapeutic agents, and new therapeutic or diagnostic assays for this new transporter protein, its associated mRNA molecules, or its associated genomic DNAs.

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Applicants have identified a human betaine/GABA transporter and have described methods for the identification of pharmacological compounds for therapeutic treatments. Pharmacological compounds which are directed against specific transporter subtypes provide effective new therapies with minimal side effects.

Elucidation of the molecular structures of the betaine/GABA transporter is an important step in the understanding of GABAergic neurotransmission. This disclosure reports the isolation; amino acid sequence, and functional expression of a DNA clone from human brain which encodes a betaine/GABA transporter. The identification of this betaine/GABA transporter will play a pivotal role in elucidating the molecular

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This invention provides a method for screening compounds to identify drugs that interact with, and specifically bind to, a human betaine/GABA transporter, which comprises preparing a cell extract from insect cells, which comprise an expression vector adapted for expression in an insect cell which vector further comprises DNA which expresses a human betaine/GABA transporter on the cell's surface, isolating a membrane fraction from the cell extract, incubating the membrane fraction with a plurality of compounds, determining those compounds which interact with and bind to the human betaine/GABA transporter, and thereby identifying compounds which interact with, and specifically bind to, the human betaine/GABA transporter.

Specifically, this invention relates to the first isolation of cDNAs encoding a betaine/GABA. In addition, the human betaine/GABA transporter has been expressed in Cos7 cells and LM tk- cell by transfecting the cells with the plasmid containing DNA encoding the human betaine/GABA transporter. The pharmacological binding properties of the encoded betaine/GABA has been determined, and its binding properties classify this protein as betaine/GABA transporter. Mammalian cell lines expressing the human betaine/GABA transporter on the cell surface have been constructed, thus establishing the first well-defined, cultured cell lines with which to study the betaine/GABA transporter.

This invention further provides a method of treating an abnormal condition such as epilepsy, migraine, ischemia, myoclonus, spasticity or chronic pain. The abnormal condition may be associated with overexpression or underexpression of the betaine/GABA transporter or may be associated with the presence of excess or deficient amounts of naturally occurring substrates, the transport of which is controlled by the

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betaine/GABA transporter. In the case of overexpression of the transporter, the abnormal condition may be treated by administering, in the form of pharmaceutical composition, a ligand which specifically binds to the betaine/GABA transporter and inhibits the transport of betaine/GABA. In the case of a naturally occurring substrate, a naturally occurring substrate may be treated by underexpression, the abnormal condition may be treated by administering, in the form of a pharmaceutical composition, a ligand which specifically binds to the transporter and enhances the transport of a natural occurring substrate. In the case of an excess amount of a naturally occurring substrate the abnormal condition may be treated by administering a ligand which may be treated by inhibiting binding, and thus transport, of competitively inhibiting substrate. Finally, in the case of a deficient amount of a naturally occurring substrate the abnormal condition may be treated by either administering a ligand which enhances binding or transporting of the natural occurring substrate or binds to the transporter and mimics the biological function of the transporter and mimics the biological function of the natural occurring substrate. In all cases the ligand is present in a pharmaceutical acceptable carrier in an amount effective to accomplish the desired effect.

This invention will be better understood by reference to the experimental details which follow, but those skilled in the art will readily appreciate that the specific experiments detailed are only illustrative, and are not meant to limit the invention as described herein, which is defined by the claims which follow thereafter.

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GENERAL DEPARTMENTS

Abbreviations: ACHC, cis- β -aminocyclohexanecarboxylic acid; GABA, γ -aminobutyric acid; HBS, quinidinoethanesulfonic acid; HEPES-buffered saline; HEPES, N-[2-(2-Hydroxyethyl)piperazine-N'-(2-ethanesulfonic acid)]; L-DABA; L-(2,4)diaminobutyric acid; GAT-1, the GABA transporter originally cloned by Guastella et al. (1990) from rat brain; GAT-2 and GAT-3, additional GABA transporters cloned from rat brain (Borden et al., 1992); hGAT-1 (Nelson et al., 1990) and hGAT-3 (Smith et al., in preparation), the human homologues of rat GAT-1 and rat GAT-3, respectively; BGT-1, the betaine/GABA transporter originally cloned from dog (Yamauchi et al., 1992); human BGT-1, the human homologue of dog BGT-1; mouse BGT-1, the mouse homologue of dog BGT-1 (termed GAT-2 by Lopez-Corcuera et al., 1992); RT-PCR, reverse transcriptase-polymerase chain reaction.

CLONING AND EXPRESSION OF A BETAINE/GABA TRANSPORTER - (BGT-1) FROM HUMAN BRAIN

MATERIALS AND METHODS

Materials: [^3H]GABA (98.9 Ci/mmol) and [^{35}S]-dATP (1200 Ci/mmol) was obtained from New England Nuclear (Boston, MA). GABA, betaine, β -alanine, phloretin, quinidine, taurine, hypotaurine, and L-DABA were from Sigma Chemical Corporation (St. Louis, MO); guvacine, nipecotic acid, NNC-711, ACHC (*cis*-3-aminocyclohexanecarboxylic acid), and OH-nipeptic acid (hydroxy nipecotic acid) were from Research Biochemicals International (RBI), 1 Strathmore Rd., Natick, Massachusetts, 01760. GES can be prepared according to the method of Fujii, et al. (1975). Cell culture media

Were obtained from Specialty Media (Lavallette, NJ); and serum was from UBI (Lake Placid, NY).

Use of PCR to Identify cDNA Libraries for Screening:

Degenerate primers were designed to amplify putative human GAT-2 cDNA clones based on sequence comparisons between conserved regions of several transporters. The sequences of the degenerate primers were 5'-TCGAATTCC(G/C)CAA(C/T)GTTG(C/A)GTT(C/T)CCCTA (sense) and 5'-TGCAGGGCGCAA(A/G)AAAGATCCTGCTGTGCGC(A/G)TC (antisense).

PCR reactions were carried out in a buffer containing 20mM Tris (pH 8.3), 50 mM KCl, 1.5mM MgCl₂, 0.001% gelatin, 2mM dNTP's, 1μM each primer, Taq polymerase, and an aliquot of a lambda phage library water, or a control plasmid for 40 cycles of 94°C. for 2 min., 40°C. for 2 min., and 72°C. for 3 min. The products were separated by electrophoresis in 1.2% agarose gels, blotted to nylon membranes (Genescreen plus; New England Nuclear, Boston, MA), and hybridized

representing the rat GAT-2 sequence (overlapping
 4 5 m e r s : s e n s e , 5 ' 5 '
 GTCCTGAACTCAGATGGCATCCAGCACCTGGTCCCTGGC (SEQ I
 No. 3); antisense, 5'-
 GCAGGAGGCACAGGACCCAGCTCCAGGCCAGGACCCAGGTGCT (SEQ. I
 No. 4). Hybridization was at 40°C. in a solution
 containing 50% formamide, 10% dextran sulfate, 5X SSC
 1X Denhardt's, and 100 µg/ml of sonicated salmon sperm
 DNA. Blots were washed at high stringency (0.1X SSC
 50°C.) and exposed to Kodak XAR film overnight with on
 intensifying screen at -70°C.

Isolation and Sequencing of Human Betaine/GABA CDNA Clones: A human striatum cDNA library in the Lambda ZAP II vector (Stratagene, La Jolla, CA) identified by PCR was screened under high stringency (50% formamide, 35

Massachusetts, 01760. GES can be prepared according to the method of Fujii, et al. (1975). Cell culture media

GAT-2 probes described above. Hybridizing lambda phage were plaque purified and converted to phagemids by in vivo excision with f1 helper phage. Nucleotide sequences of double-stranded DNAs in pBluescript were analyzed by the Sanger dideoxy nucleotide chain-termination method (Sanger, 1977) using Sequenase (U.S. Biochemical Corp., Cleveland, Ohio). A cDNA clone (designated hSia) identified as representing the entire coding region of a novel human transporter was subcloned into a eukaryotic expression vector (modified from pcEXV-3, Miller and Germain, 1986) as a 3.1 kb XbaI/Sall fragment.

Transfection: Transient transfections of COS cells were carried out using DEAE-dextran with DMSO according to the method of Lopata et al. (1984), with minor modifications, or according to the method of Smith et al. (1992) with minor modifications. COS cells grown in 75cm² or 150cm² flasks in DMEM with 10% bovine calf serum, 100 U/ml penicillin G, and 100 µg/ml streptomycin sulfate (37°C, 5% CO₂) were transfected using DEAE-dextran. On the day following transfection the cells were split into 24-well assay plates, and transport was measured 24 hours later.

Stable transfection: Stable cell lines expressing hGGT-1 were generated in LM(tk) cells using the calcium phosphate method and selection in G-418, as described previously (Weinshank et al., 1992). Cells were grown under standard conditions (37°C, 5% CO₂) in Dulbecco's modified Eagles's medium (GIBCO, Grand Island, NY). Similar results were obtained with transient and stable transfectants.

Northern Blot Analysis of hGGT-1 mRNA: Human brain total RNA was purchased from Clontech (Palo Alto, CA). Denatured RNAs (25µg) were separated by electrophoresis

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in 1.0% agarose gels containing 2.7% formaldehyde and then transferred to a Genescreen Plus nylon membrane (Dupont-NEN, Boston, MA) by overnight capillary blotting in 10X SSC. Prehybridization was for 1-2 hours at 42°C in a solution containing 50% formamide, 1M sodium chloride, 10% dextran sulfate and 1.0% SDS. The blot was hybridized overnight at 42°C with Up-labeled randomly-primed probe (1.5 Kb NcoI fragment of hGGT-1; Prime-It II Kit, Stratagene, La Jolla, CA) in prehybridization mixture containing 100 µg/ml sonicated salmon sperm DNA. The blot was washed successively in 2X SSC/2% SDS for 1 hour, 1X SSC/2% SDS for 45 minutes, and 0.2X SSC/2% SDS for 45 minutes at 65°C, then exposed to Kodak XAR-5 film with one intensifying screen at -80°C for 10 days.

To determine the regional localization of hGGT-1 mRNA, a Northern blot containing mRNA from multiple brain regions (Clontech) was hybridized with the hGGT-1 probe (see above) overnight at 42°C in a solution containing 5X SSPE, 10X Denhardt's, 50% formamide, 2% SDS, and 100 µg/ml sheared salmon sperm DNA. The blot was washed at room temperature for 40 minutes in 2X SSC/0.05% SDS, then at 50°C for 40 minutes in 0.1X SSC/0.05% SDS. After overnight exposure to Kodak XAR-5 film, the blot was reprobed for β-actin to confirm that equal amounts of RNA were present in each lane.

Transport assay: Transport by attached cells was measured as described previously (Borden et al. 1992), with the following modifications. Cells grown in 24-well plates (well diameter = 18mm) were washed 3X with HEPES-buffered saline (HBS, in mM: NaCl, 150; HEPES, 20; CaCl₂, 1; glucose, 10; KCl, 5; MgCl₂, 1; pH 7.4) and allowed to equilibrate on a 37°C slide warmer. After 10 minutes the medium was removed and unlabeled drugs in HBS were added (450 µl/well). Transport was initiated by adding 50 µl per well of a concentrated

35 10 minutes the medium was removed and unlabeled drugs in HBS were added (450 µl/well). Transport was initiated by adding 50 µl per well of a concentrated

solution of [³H]GABA in HBS (final concentration = 50 nM). Non-specific uptake was defined in parallel wells with 1 mM unlabeled GABA, and was subtracted from total uptake (no competitor) to yield specific uptake; all data represent specific uptake. Plates were incubated at 37°C for 10 minutes, then washed rapidly 3x with ice-cold HBS, using a 24-position plate washer (Brändel, Gaithersburg, MD; model PW-12). Cells were solubilized with 0.05% sodium deoxycholate/0.1N NaOH (0.25 ml/well), an aliquot neutralized with 1N HCl, and radioactivity was determined by scintillation counting. Protein was quantified in an aliquot of the solubilized cells using a BIO-RAD protein assay kit, according to the manufacturer's directions.

Transport was also measured in suspension. Briefly, transient (COS-7) or stable (LH) transfectants were removed from culture plates with trypsin/EDTA, and transferred to suspension culture. The cells were grown in a temperature-controlled shaking incubator, using a medium containing methylcellulose. To measure transport the cells were washed by centrifugation, and resuspended in HBS. The assay was performed in 96-well microtiter plates (total volume = 0.25ml/well). The cells were incubated with 50nM [³H]GABA and required drugs for 10 minutes at 37°C, then collected using a Brändel harvester. Cell-associated radioactivity retained on the filters was determined by scintillation counting.

Data Analysis: Competition curves were conducted in duplicate, using 10 concentrations of unlabeled drug. IC₅₀ values (concentrations resulting in 50% inhibition of uptake) were derived using software from GraphPad Inplot (San Diego, CA). Data were not corrected for the concentration of radioligand since [³H]GABA was employed at a concentration well below its K_i; however,

since initial rates were not studied, data are presented as IC₅₀. All data throughout the paper represent means ± SEM.

5 **In Situ Hybridization:** Male mice (Charles River) were decapitated and the brains rapidly removed and frozen in isopentane. Coronal sections were cut at 11 µm on a cryostat, thaw mounted onto poly-L-lysine coated glass slides and stored at -80°C until used. Immediately prior to hybridization, the tissues were fixed in 4% paraformaldehyde, treated with 5 mM dithiothreitol, acetylated in 0.1 M triethanolamine containing 0.25% acetic anhydride, delipidated with chloroform and dehydrated in graded ethanol.

10 Antisense and sense oligonucleotide probes (45mers), corresponding to nucleotides 1894-1938 of the 3'-untranslated region of the mouse betaine transporter (Lopez-Corcuera et al.; 1992) were synthesized on a Cyclone Plus DNA synthesizer (Milligen/Bioscience) and gel-purified. The probes were 3'-end labeled with ³⁵S-ATP (1200 Ci/mmol, New England Nuclear, Boston, MA) to a specific activity of 10⁹ dpm/µg using terminal deoxynucleotidyl transferase (Boehringer Mannheim; Indianapolis, IN). The radiolabeled probes were purified on Biospin 6 chromatography columns (Bio-Rad; Richmond, CA), and diluted in hybridization buffer to a concentration of 1.5 x 10⁶ cpm/µl. The hybridization buffer consisted of 50% formamide, 4X sodium citrate (1X SSC = 0.15 M NaCl and 0.015 M sodium citrate), 1X Denhardt's solution (0.2% polyvinylpyrrolidone, 0.2% Ficoll, 0.2% bovine serum albumin), 50 mM dithiothreitol, 0.5 mg/ml salmon sperm DNA, 0.5 mg/ml yeast tRNA, and 10% dextran sulfate. One hundred µl of the radiolabeled probe was applied to each section, which was then covered with a Parafilm coverslip. Hybridization was carried out overnight in

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humid chambers at 42°C. The following day the sections were washed in two changes of 2X SSC for one hour at room temperature, in 2X SSC for 30 min at 50-60°C, and finally in 0.1X SSC for 30 min at room temperature.

Tissues were dehydrated in graded ethanol and apposed to Kodak XAR-5 film for 4 to 11 days at -20°C, then dipped in Kodak NFB3 autoradiography emulsion diluted 1:1 with 0.2% glycerol water. After exposure in light-tight boxes at 4°C for 3 weeks, the slides were developed in Kodak D-19 developer, fixed, and counterstained with hematoxylin and eosin.

RESULTS

Cloning of the Human Betaine/GABA Transporter

A human striatum library (Stratagene) was screened at high-stringency with probes obtained from the rat GAT-2 transporter cDNA; positive plaques were purified by successive screening at high stringency. Four cDNA clones were isolated (hs1a, hs13a, hs26a, and hs38a) that exhibited significant homology to the nucleotide sequence of rat GAT-2, but were too dissimilar to represent species homologues of this clone. One of these, hs1a, was determined by sequence analysis to contain the full coding region of a novel transporter; the complete nucleotide sequence and predicted amino acid sequence of this clone are shown in Figures 1A-1D. The nucleotide sequence of the coding region of hs1a displayed a high degree of identity to dog BGT-1 (89%; Yamauchi et al., 1992) and the related mouse cDNA (86%; Lopez-Corcuera et al., 1992). Translation of a long open reading frame of hs1a predicts a protein of 614 amino acids with 12 putative transmembrane domains. As expected, the predicted amino acid sequence displayed a higher degree of identity with dog BGT-1 (91%) and mouse BGT-1 (87%; Lopez-Corcuera et al., 1992), than with rat GAT-2 (70%) or rat GAT-3 (66%), the next closest relatives (see Figures 2A-2G). This finding, and the ability of hs1a to confer high-affinity GABA transport activity following transfection into host cells (see below), together suggest that the new clone represents the human homologue of dog BGT-1; accordingly, we refer to it as human BGT-1.

Two potential sites for N-linked glycosylation are present in the Predicted extracellular loop between TMs III and IV of human BGT-1, as in dog and mouse. Despite their high overall amino acid identities,

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alignment of human, mouse, and dog BGT-1 sequences reveals several non-conservative amino acid substitutions in the human sequence (Figures 2A-2G). Differences are also observed in the number and location of potential sites for phosphorylation by casein kinase II and protein kinase C between the three homologues (data not shown). The functional significance of these variations is not yet known, but they could potentially affect the pharmacological properties and/or regulation of the transporter.

Expression and Pharmacological Characterization of Human Betaine/GABA Transporter.

Transient transfection of COS-7 cells with hS1A resulted in a 9-fold increase in the specific uptake of [³H]GABA as compared to non-transfected controls (Figure 3). The GABA transporter encoded by hS1A was also studied in stably transfected, LM(tk) cells, as described in Methods. The highest level of expression was observed in clone 3 (termed L-hBGT-1-3), which was used for subsequent characterization. As shown in Figures 4A - 4D, [³H]GABA uptake by L-hBGT-1-3 was increased 20-fold as compared to non-transfected cells. Thus, enhanced uptake of [³H]GABA was observed with both transient and stable transfectants. [³H]GABA uptake by L-hBGT-1-3 was decreased >95% in medium lacking either Na⁺ or Cl⁻ (data not shown), similar to results obtained with the dog homologue (Yamauchi et al., 1992). To determine the pharmacological specificity of hS1A, a number of compounds were examined for their ability to inhibit the transport of [³H]GABA by L-hBGT-1-3 (Table 1); the published data for the dog and mouse clones are shown for comparison. GABA itself was the most potent inhibitor, displaying an IC₅₀ of 16 μM. The next most potent inhibitors were phloretin, L-DABA, hypotaurine, and NNC-711, with IC₅₀

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values between 160 and 600 μM. The other compounds tested, including betaine, displayed IC₅₀'s between 1 and 2 mM. Taurine was the weakest agent tested, with an IC₅₀ > 10 mM.

Table 1. Pharmacological profile of betaine/GABA transporters from human, dog, and mouse.

	IC ₅₀ , μ M	dog BGT-1 ¹	mouse GAT-2 ¹
GABA	36±3	93	79
phloracetin	160±18	200	37
L-DABA	354±42	4,700	
hypotaurine	380±9		
NNC-711	622±265		
betaine	934±22	398	206
quinidine	1,190±96	325	49
β -alanine	1,320±224	2,400	1,900
GES	1,520±88		
ACHC	1,850±363		
guvacine	1,870±387		2,800
(\pm)nipecotic acid	2,350±253	4,700	8,000
hydroxynipecotic acid	2,590±324		
taurine	10,600±2190		

Regional Localization of BGT-1 mRNA in Brain

To define the size of the transcript encoding human BGT-1 we prepared a Northern blot of total human brain RNA. Hybridization with a radiolabeled fragment of hBGT-1 revealed a single \approx 3.1 kb transcript (Figure 4A); this finding, and the pharmacological data, suggest that hS1a represents a full-length cDNA. Detection of the hBGT-1 transcript in total RNA from human brain confirms the differential distribution of BGT-1 mRNA in human and dog (see Yamuchi et al., 1992).

To map the distribution and abundance of hBGT-1 transcripts within the brain, we carried out Northern blot analysis of mRNA isolated from eight human brain regions. The \approx 3.1 kb transcript was present at similar abundance in all regions examined (Figure 4B), revealing a wide pattern of distribution for hBGT-1 in human brain. The transcript was also detected in human kidney mRNA by RT-PCR (data not shown).

To determine the localization of BGT-1 mRNA at the cellular level, we employed *in situ* hybridization. Due to the paucity of well-preserved human brain tissue, we performed the localization studies in mouse brain using oligonucleotide probes to mouse BGT-1, as described in Methods. Hybridization with radiolabeled antisense probes revealed low to moderate labeling in all brain regions (Figure 5A); in contrast, no autoradiographic signal, either on film or in emulsion-dipped sections, was observed following hybridization with sense probes (Figure 5B). At the microscopic level, silver grains were observed over many neuronal perikarya, in all regions of the mouse brain. The largest accumulations of grains over individual neurons were seen in the lateral septum (Figure 5A, C), and the preoptic nucleus of the anterior hypothalamus (Figure 5A, D).

Inhibition of [³H] GABA uptake in stably transfected LM (tk⁻). Each value is the mean \pm standard error of at least three experiments.

Inhibition of [³H] GABA uptake in oocytes (Yamuchi et al., 1992); IC₅₀ values (except for GABA) are estimated from per cent inhibition at a single concentrations.

Inhibition of [³H] GABA uptake in oocytes (Lopez-Corcuera et al., 1992); IC₅₀ values (except for GABA) are estimated from per cent inhibition at one or two concentrations.

In the lateral septum, there was a strip of labeled medium-sized neurons ($\approx 11\text{-}18 \mu\text{m}$ in long diameter), which extended ventrolaterally from near the midline to the lateral ventricle (Figure 5C). In the hypothalamus, the most heavily labeled neurons, 10-13 μm in long diameter, were found in the preoptic nucleus (Figure 5D). While it is often difficult to determine localization of silver grains over glial cells, due to the small area of cytoplasm, the antisense oligonucleotide probe used in the current study did not appear to hybridize to glial cells in the mouse brain.

Discussion

In this communication we describe the cloning and expression of a human betaine/GABA transporter from a brain cDNA library. This transporter displays 91% and 87% amino acid identity with dog BGT-1 (Yamauchi et al., 1992) and the related mouse clone (Lopez-Corcuera et al., 1992), respectively. These values are similar to the amino acid identities between human, rat, and dog taurine transporters (91-93%), rat and human dopamine transporters (92%), and between rat and human homologues of the GABA transporter GAT-3 (95%), though they are slightly less than the identity between the species homologues of the GABA transporter GAT-1 (97-99%). These data indicate that the dog betaine/GABA transporter, the related mouse clone, and the human clone described here are species homologues; accordingly, we adhere to the original nomenclature of Yamauchi et al. (1992) and refer to all three clones as BGT-1.

The pharmacologic profiles of the three BGT-1 transporters bear some similarities, but also significant differences. The affinities of GABA and β -alanine are similar among the three transporters, varying by only 2- to 3-fold. Similarly, betaine displays 2-fold and 5-fold selectivity for mouse BGT-1 as compared to the dog and human clones, respectively. In contrast, other drugs show greater variation in affinity. For example, phloretin show 4- to 5-fold selectivity for mouse BGT-1 as compared to dog and human BGT-1. Quinidine is the most selective of the compounds tested, displaying potency at mouse BGT-1 that is 7-fold and 25-fold greater than the dog and human BGT-1, respectively. While all three clones show higher affinity for GABA than for betaine (the presumed natural substrates), the selectivity is 3- to 4-fold

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for the mouse and dog clones, but 26-fold for human BGT-1. The similar affinities of GABA and β -alanine at the three clones suggest that the differences observed for some of the drugs are not due to methodological differences between laboratories, such as the use of fibroblasts or oocytes, or differences in the time and temperature of transport measurements. Rather, they suggest that species differences in transporter structure result in differential drug sensitivities. Pharmacological differences attributable to sequence differences are well known in G-protein-coupled receptors (Adham et al., 1992; Kao et al., 1992; Link et al., 1992). The current data suggest that this phenomenon also occurs in transporters and underscores the importance of using human clones in drug development, as has been discussed previously (Hartig, 1992).

The ability of BGT-1 to utilize both GABA and betaine as substrates (Yamauchi et al., 1992) suggests that it might serve multiple physiological roles. Yamauchi et al. (1992, and references therein) noted that the plasma levels of betaine (180 μ M) are considerably higher than those of GABA (1 μ M) and thus concluded that, despite the 4-fold higher affinity of the transporter for GABA than for betaine, betaine is the physiological substrate in the renal medulla. Northern blots did not reveal the presence of BGT-1 mRNA in dog brain, suggesting that in this species the action of betaine is limited to that of osmoregulation in the kidney; however, more sensitive techniques such as PCR will be required to determine whether BGT-1 is truly absent from dog brain, or if it is simply present at low levels.

The presence of BGT-1 mRNA in the human and mouse brains suggests that, in these species, betaine also

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functions in regulating neural function. Betaine has been detected in brain where it is thought to serve an osmoregulatory function (Heilig et al., 1989). It is normally present in low concentrations but levels are increased following salt-loading (Heilig et al., 1989). Because the brain is suspended in a rigid container (i.e., the skull), volume regulation is critical to the proper functioning of the central nervous system. It is of interest that hGBT displays a relatively high degree of sequence identity (61%) with the transporter for taurine (Smith et al., 1992b), a major osmoregulator in the central nervous system.

GABA is the major inhibitory neurotransmitter in the mammalian brain and heterogeneity of GABA transporters is well documented (see Introduction). A role for BGT-1 in GABAergic transmission is supported by the presence of BGT-1 mRNA in mouse and human brain and by the finding that, when assayed under identical conditions, the affinity of GABA for hBGT-1 is within 2- to 3-fold of its affinities for GAT-1, GAT-2, and GAT-3 (Borden et al., submitted). Further, as described above, human BGT-1 displays 25-fold higher affinity for GABA than for betaine, and is thus a high-affinity GABA transporter. Since the dog transporter is capable of utilizing both betaine and GABA as substrates, this additional function for BGT-1 in brain would not have required extensive structural changes in the transporter.

In situ hybridization and Northern blot studies revealed a wide-spread distribution of BGT-1 mRNA in the mouse and human brain which does not closely match the localization of GABAergic pathways. This lack of correspondence suggests that BGT-1 might not play a role in terminating the action of GABA at the synapse; rather, it may serve to sequester GABA that has

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diffused away from synaptic regions, thereby assuring the fidelity of transmission. The development of specific, high-affinity inhibitors of BGT-1 should help elucidate the role of this transporter in nervous function, and may represent novel therapeutic agents.

The cellular localization of BGT-1 in the human brain remains to be determined. It should be noted that in contrast to the localization in mouse brain, which suggests a neuronal distribution, rat BGT-1 mRNA is more abundant in primary rat glial cultures than in primary neuronal cultures (Borden et al., submitted). A transcript with a low copy number per cell distributed among many cells may be difficult to detect by *in situ* hybridization; therefore, the apparently neuronal distribution of BGT-1 mRNA in mouse brain does not preclude glial expression. The wide distribution of BGT-1 mRNA we observe in human brain would be consistent with BGT-1 expression in brain astrocytes as well as neurons.

Alterations in osmoregulation and in GABAergic transmission have been implicated in a variety of neuropathological and psychiatric conditions. Our cloning of a human betaine/GABA transporter will help elucidate its role in the central nervous system, and will further our understanding of the roles of GABA and betaine in neural function. Additionally, the cloned transporter will aid in the development of specific, high-affinity ligands for this transporter: The use of human gene products in the process of drug development offers significant advantages over those of other species, which may not exhibit the same pharmacologic profiles. The development of such drugs may be useful in a variety of conditions, including (though not

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restricted to) epilepsy, migraine, ischemia, myoclonus, spasticity, and the treatment of chronic pain.

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RE-EVALUATION OF GABA TRANSPORT IN NEURONAL AND GLIAL
CELL CULTURES:
CORRELATION OF PHARMACOLOGY AND mRNA LOCALIZATION

It is now well established that sodium-dependent neurotransmitter transporters are key components of the synaptic machinery which mediates chemical transmission in the vertebrate nervous system. Neurotransmitter transporters may serve a number of important functions in synaptic transmission, including termination of synaptic transmission, prevention of the spread of transmitter (thereby assuring the fidelity of transmission), and re-utilization of neurotransmitter (see Krosgaard-Larsen, 1987 for review). In addition, transporters may also work in reverse, releasing neurotransmitter in a calcium-independent manner (Levi and Raiteri, 1993; Attwell et al., 1993). Available data suggest that neurotransmitter transporters are located on the plasmalemma of presynaptic terminals and surrounding astroglial cells, though the relative contribution of each remains to be established.

Pharmacological inhibition of neurotransmitter transport provides a means for increasing neurotransmitter levels in the synapse, thereby enhancing synaptic transmission. The therapeutic utility of this approach is exemplified by the classical tricyclic antidepressants which inhibit the uptake of the monoamine neurotransmitters such as norepinephrine and serotonin. In contrast, less is known regarding the therapeutic potential of inhibiting the transport of other classes of neurotransmitter, such as the inhibitory amino acid transmitters.

γ -Aminobutyric acid (GABA) is the major inhibitory neurotransmitter in the mammalian brain. Modulation of GABAergic activity has important therapeutic benefit as evidenced by drugs such as benzodiazepines and barbiturates which bind to allosteric modulatory sites on the GABA_A receptor, thereby increasing the affinity for GABA. Inhibition of GABA transport represents a novel approach to increasing GABAergic activity which may prove useful in the treatment of epilepsy, anxiety, and other neuropsychological disorders. An important step in the realization of this goal is a more thorough understanding of the properties of GABA transporters.

Cell cultures derived from mammalian brain have proven to be useful models for the study of GABA transport and lead to the classification of distinct neuronal and glial GABA transporter systems (see Krosgaard-Larsen, 1987 for review). These two transport systems are distinguished by AChC and L-DABA, which have higher affinity for the neuronal transporter, and by β -alanine, which shows selectivity for the glial transporter. Other transport inhibitors such as nipecotic acid, hydroxynipecotic acid, and guvacine show varying degrees of selectivity for the glial transporter (Krosgaard-Larsen, 1987).

Molecular biology has greatly increased our understanding of sodium-dependent neurotransmitter transporters (see Amara and Arriza, 1993, for review). The first neurotransmitter transporter to be cloned was a high affinity GABA transporter isolated from rat brain, termed GAT-1 (Guastella et al., 1990), which displays a pharmacological profile consistent with the "neuronal" transporter. Subsequently two additional High-affinity GABA

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transporters, GAT-2 and GAT-3 were cloned from rat brain (Borden et al., 1992); a clone identical to GAT-1 was described by Clark et al. (1992) and termed GAT-B. An additional member of the GABA transporter family was cloned from dog kidney and transports both the osmolyte betaine and GABA, and was thus referred to as BGT-1 (Yamauchi et al., 1992). We have recently cloned the human homologue of BGT-1 from a human brain cDNA library (L.A. Borden, K.E. Smith; E.L. Gustafson, T.A. Branchek, and R.L. Weinshank, unpublished observations), confirming its expression in the central nervous system. Clones for all four GABA transporters have been identified in mice, although a different nomenclature was employed (Liu et al., 1991).

In contrast to GAT-1, the relationship of GAT-2, GAT-3, and BGT-1 to the pharmacologically characterized neuronal and glial transport systems is not understood. While GAT-2 and GAT-3 display high affinity for β -alanine and low affinity for ACHC, suggesting a similarity to the glial transporter, their overall pharmacological profile indicates that they are distinct from this site. Additionally, the observation that GAT-3/GAT-B is located in neurons (Clark et al., 1992; M.M. Durkin, E.L. Gustafson, K.E. Smith, L.A. Borden, P.R. Hartig, R.L. Weinshank, and T.A. Branchek, unpublished observations) indicates that neuronal transport is not limited to GAT-1, and that β -alanine sensitivity is not unique to glial GABA transport.

An additional level of complexity results from the heterogeneity of astrocytes. Two types of astrocytes, termed Type 1 and Type 2, have been described in cell cultures (for reviews see Raff, 1989; Miller et al., 1989). Interestingly, it has been suggested that

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Type 2 astrocytes and their precursor, termed O-2A, display a "neuronal-like" GABA transport pharmacology (Levi et al., 1983; Reynolds and Herschkowitz, 1984; Johnstone et al., 1986), suggesting that GAT-1 may not be restricted to neurons. A failure to recognize and/or distinguish these cell types in many older studies complicates their interpretation.

To gain a better understanding of the contribution of the cloned GABA transporters to neuronal and glial transport systems, we have undertaken a combined pharmacological and molecular biological study using cell cultures derived from rat brain. We first defined the pharmacological profile of the four cloned GABA transporters (i.e., GAT-1, GAT-2, GAT-3, and BGT-1), and a related member of this family, the taurine transporter (TAUT; Smith et al., 1992). Next, we examined GABA transport activity in neuronal cultures, and in both Type 1 and O-2A/Type 2 astrocytic cell cultures, and compared their profiles to those of the cloned transporters. Last, we examined these cultures for the presence and relative abundance of mRNA for each of the four GABA transporters and TAUT.

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MATERIALS AND METHODS

Materials: [³H]GABA² (\approx 90Ci/mmol) and [³H]taurine (21.9Ci/mmol) were obtained from New England Nuclear (Boston, MA). GABA, taurine, hypotaurine, L-DABA (L-(2,4)diaminobutyric acid), poly-D-lysine hydrobromide (average molecular weight, 67,700), arachidic acid and β -alanine were from Sigma Chemical Corporation (St. Louis, MO); guvacine, nipeptic acid, hydroxynipeptic acid, and NNC-711 were from RBI (Natick, MA). ACHC (cis-3-amino cyclohexanecarboxylic acid) was provided by Research Biochemical International as part of the Chemical Synthesis Program of the National Institute of Mental Health contract 278-90-0007 (BS). 'GES' was a generous gift of Dr. J. Barry Lombardini (Department of Pharmacology, Texas Tech University). Cell culture media were obtained from Specialty Media (Lavallette, NJ), and serum was from UBI (Lake Placid, NY). Cell cultures were maintained at 37°C in a humidified 95% air/5% CO₂ atmosphere.

Preparation of primary rat astrocyte cell cultures: Primary glial cultures were established from newborn Sprague-Dawley rat brains. Brains minus cerebella were removed aseptically and carefully dissected free of meninges. A single-cell suspension was made by mincing the brains, then incubating them with 0.25% trypsin/1 mM EDTA for 2-3 minutes. Following inactivation of the trypsin by addition of complete medium (DMEM containing 10% fetal calf serum, 100 U/ml penicillin G, and 100 µg/ml streptomycin sulfate), the cells were allowed to settle and the supernatant decanted; this procedure was then repeated. The cells were dissociated by trituration through a serological pipet. Separate procedures were then used for the preparation of Type-1 and O-2A/Type-2 astrocyte cultures, as will now be described.

For the preparation of Type-1 astrocyte cultures, cells were plated onto uncoated 75 cm² flasks at low density (1 brain per 10 flasks, or approximately 8×10^6 cells/cm²). The medium was changed the following day and twice a week thereafter. After 2-3 weeks the Type 1 astrocytes formed a confluent monolayer, with only minimal contamination of O-2A/Type-2 cells. The cells were then split into 24-well plates (typically, each 75 cm² flask was split into six 24-well plates) and 1-2 weeks later, transport was measured as described above. Such cultures stained heavily with an anti-GFAP antibody (not shown).

Cultures highly enriched in O-2A/Type-2 cells were prepared from mixed astrocyte cultures which consisted of a monolayer of Type 1 cells upon which rested large numbers of O-2A/Type 2 cells. It had previously been shown that O-2A/Type 2 cells could be purified from such cultures by overnight shaking, which releases the O-2A/Type 2 cells into the medium (McCarthy and Devellis, 1980). However, we found this method to be impractical for the large numbers of cells required for the present study, and thus sought a more rapid method of isolation. The same brain cell suspensions as described above were plated at high density (1 brain per 75 cm² flask, or approximately 8×10^6 cells/cm²) into flasks coated with poly-D-lysine (10 µg/ml). After 24 hours the medium was replaced and the cultures were subsequently fed twice a week. After 2-3 weeks the cultures consisted of a large number of O-2A/Type-2 cells lying on a monolayer of Type-1 astrocytes. The mixed Type-1 and O-2A/Type-2 astrocyte cultures were washed with PBS, then incubated with trypsin/EDTA for 20-30 seconds with vigorous "smacking"; this technique selectively detached the O-2A/Type-2 cells. Complete medium was added to the flasks and the cell suspension was removed gently, care being taken to not disrupt the

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underlying Type 1 astrocyte monolayer. The cells were pelleted at low speed, resuspended in complete medium, and added to 24-well plates coated with poly-D-lysine (10 µg/ml). Typically, the cells collected from eight 5 75 cm² flasks were added to twelve 24-well plates; increasing the cell density resulted in greater contamination of Type-1 astrocytes. The cells were used for transport assays two days later, by which time about 85% of the cells had extended processes with the typical morphology of O-2A/Type-2 astrocytes; such 10 cells displayed varying intensities of staining with an anti-GFAP antibody (not shown), similar to previous results (Lillien and Raff, 1990). No attempt was made to distinguish or separate O-2A precursors from the more differentiated Type 2 astrocytes.

Preparation of primary rat neuronal cell cultures:

Primary neuronal cultures were prepared as described previously (Vayssi et al., 1990). Brains were removed aseptically from E17 embryonic Sprague-Dawley rats brains, carefully dissected free of meninges, and kept 15 on ice. A single-cell suspension was made by mincing the brains, followed by trituration through a serological pipet. The large clumps were allowed to settle, and the supernatant diluted with medium (DMEM/F-12 (1:1) containing 10% fetal calf serum, 100 U/ml penicillin G, 100 µg/ml streptomycin sulfate, 10 µg/ml insulin (porcine or bovine), supplemented with 45 mM KCL), and added to 24-well plates (coated with 10 µg/ml poly-D-lysine) at a density of approximately 20 2x10³ cells/cm². On day three cytosine β-D-arabinofuranoside (3µM) was added to control the proliferation of non-neuronal cells. The cultures were used for transport assay approximately one week after plating.

Transient transfection: Transient transfection was carried out in COS cells as previously described (Smith et al., 1992), with the following modifications. COS

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cells grown in 75cm² or 150cm² flasks in DMEM with 10% bovine calf serum, 100 U/ml penicillin G, and 100 µg/ml streptomycin sulfate (37°C, 5%CO₂) were transfected using DEAE-dextran. On the day following transfection the cells were split into 24-well assay plates coated with poly-D-lysine (10 µg/ml), and transport was measured 24 hours later.

During the course of this work we noted that compounds typically displayed higher affinity in stable transfections in LM(tk') cell hosts than in transient transfections in COS cell hosts (L. Borden, unpublished observations). The difference in affinity was typically 3-fold, though this varied from clone to clone. Importantly, expression levels did not appear to alter the order of potencies. This phenomenon should be considered when comparing data using different expression systems.

Transport in attached cells: GABA transport by attached cells was measured as described previously (Borden et al., 1992), with the following modifications. Cells grown in 24-well plates (well diameter = 18mm) were washed 3X with HEPES-buffered saline (HBS, in mM: NaCl, 150; HEPES, 20; CaCl₂, 1; glucose, 10; KCl, 5; MgCl₂, 1; pH 7.4) and allowed to equilibrate on a 37°C slide warmer. After 10 minutes the medium was removed and unlabeled drugs in HBS were added (450 µl/well). Transport was initiated by adding 50 µl per well of a concentrated solution of [³H]GABA in HBS (final concentration = 50 nM). Non-specific uptake was defined in parallel wells with 1 unlabeled GABA (10mM for Type 1 astrocytes), and was subtracted from total uptake (no competitor) to yield specific uptake; all data represent specific uptake. Plates 35 were incubated at 37°C for 10 minutes, then washed rapidly 3X with ice-cold HBS, using a 24-position plate washer (Brandeel, Gaithersburg, MD; model PW-12). Cells

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were solubilized with 0.05% sodium deoxycholate/0.1N NaOH (0.25 ml/well), an aliquot neutralized with 1N HCl, and radioactivity was determined by scintillation counting. Protein was quantified in an aliquot of the solubilized cells using a BIO-RAD protein assay kit, according to the manufacturer's directions.

5 Brain Aggregate Preparation: Brain aggregates were prepared as described in Forray and El-Fakahany (1990), with minor modifications. Briefly, adult rat brains were removed from the skull and the cerebral cortex was dissected and placed in ice-cold HBS. The tissue was forced through a nylon mesh bag (200 μ m pore; Nitex) followed by passage through a second nylon bag (110 μ m pore size; Nitex). The preparation was washed once by centrifugation, then resuspended in HBS.

10 Transport by brain aggregates: GABA transport by brain aggregates was determined in suspension in 96-well microtiter plates (total incubation volume = 250 μ l), using an assay similar to that employed for membrane receptor binding (see Zgombick et al., 1991). Briefly, [3 H]GABA (final concentration = 50nM) and unlabeled drugs were added to 96-well plates (Corning), and transport was initiated by the addition of brain aggregates. Non-specific uptake was determined with 1 mM unlabeled GABA. The reaction was continued for 10 minutes (37°C), then terminated by rapid filtration through pre-soaked (0.5% polyethyleneimine) GF/B glass fiber filters, using a Brandel48R cell harvester. The filters were washed with ice-cold HBS, punched into vials, and radioactivity determined by scintillation counting. Protein was determined in an aliquot of the aggregate preparation using the BIO-RAD protein assay kit.

15 Northern Blot Analysis of Transporter mRNAs: For a 1 cellular RNA was isolated from cultured cells using a modification of the method of Chirgwin et al. (1979). Briefly, cells were rinsed with ice-cold phosphate-

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buffered saline and lysed in guanidine isothiocyanate (5-10 mls/100mm plate). Lysates were drawn twice through a 20-gauge needle to shear genomic DNA, and RNA was collected by centrifugation through 5.3M cesium chloride (MacDonald et al., 1987). Rat brain poly A+ RNA was purchased from Clontech (Palo Alto, CA).

5 Denatured RNA samples (5-25 μ g) were separated by electrophoresis in 1.0% agarose gels containing 2.7% formaldehyde. RNAs were transferred to Genescreen Plus nylon membranes (Dupont-NEN, Boston, MA) by overnight capillary blotting in 10X SSC. Northern blots were rinsed and then baked for 2 hours at 80°C under vacuum. Prehybridization was for 1-2 hours at 42°C in a solution containing 50 \times formamide, 1M sodium chloride 10 \times dextran sulfate and 1.0% SDS. Blots were hybridized overnight at 42°C with 32 P-labeled randomly-primed probes (Prime-It II, Stratagene, La Jolla, CA) in prehybridization mixture containing 1.00 μ g/ml sonicated salmon sperm DNA. The blots were washed successively in 2X SSC/2% SDS, 1X SSC/2% SDS, and 0.2X SSC/2% SDS at 65°C, then exposed to Kodak XAR-5 film with one intensifying screen at -80°C for up to one week.

15 To facilitate quantitative comparisons of signal intensities between transporters, cDNA fragments of the same size (\approx 1.5 kb) were prepared as templates for random prime labeling of GAT-1, GAT-2, GAT-3, and TAUT cDNAs, and the specific activity of each probe was determined by TCA precipitation (Sambrook et al., 1989) prior to hybridization. Specific activities ranged from 1.5-2.5 \times 10 9 dpm/ μ g DNA for all probes. Since the cDNA encoding the rat betaine/GABA transporter was not available, an 8450 bp fragment was generated by PCR (see below), subcloned, sequenced, radiolabeled, and used for hybridization of Northern blots as described. Since this fragment of rBGAT-1 is much smaller than the

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other probes, levels of rBGTr-1 transcripts cannot be visually compared with those of GAT-1, GAT-2, GAT-3, and TAUT.

5 After hybridization with transporter cDNAs, all blots were reprobed for the constitutive mRNA encoding cyclophilin (IB15; Danielson et al., 1988) to confirm that equal amounts of RNA were present in each lane. Cloning a fragment of the rat BGTr-1 primers based on the nucleotide sequence of the mouse betaine/GABA transporter (Lopez-Corcuera et al., 1992; termed "GAT2" by authors) were used to amplify a fragment of rBGTr-1 from rat brain cDNA using PCR. The primers represent nucleotides 268-296 (sense) and 715-740 (antisense) of the mouse sequence (Lopez-Corcuera et al., 1992). First strand cDNA was synthesized from rat brain poly A+ RNA using superscript reverse transcriptase (BRL, Gaithersburg, MD). PCR amplification was carried out in a buffer containing 10mM Tris (pH 8.3), 50 mM KCl, 1.5mM MgCl₂, 0.01% gelatin, 0.2mM each dNTP, 1μM each primer, Tag polymerase, and either first strand cDNA, RNA, or water for 30 cycles of 94°C/2 min, 60°C/2 min, 72°C/3 min. The ≈450 bp PCR product was separated by agarose gel electrophoresis, isolated on DE81 paper and ligated into PUC18. A portion of the reaction was blotted to a nylon membrane (Zeta-Probe GT; Bio-Rad Laboratories, Richmond, CA) and hybridized as described below with a ³²P-labeled oligonucleotide (45mer) representing the mouse BGTr-1 (Lopez-Corcuera et al., 1992) to confirm its identity. Sequence analysis of the subcloned fragment confirmed that it encoded a portion of the rBGTr-1; the fragment exhibited 85-94% nucleotide identity and 87-96% amino acid identity with dog, human, and mouse BGTr-1 cDNAs, but only 72% nucleotide identity (68% amino acid identity) with the next closest relative, rat GAT-2. This fragment was

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subsequently reisolated from a single transformant and used in Northern blot hybridizations of rBGTr-1 mRNA.

Quantitation of Northern Blots: Autoradiograms were scanned using a Color One Scanner (Apple) and analyzed on an Apple Macintosh computer using Image 1.43 software (NIH). Band intensities were corrected for the amount of mRNA as determined by hybridization to the constitutive mRNA encoding cyclophilin, then normalized to the amount of GAT-1 present in neuronal cultures (for neurons and astrocyte cultures), or the amount of GAT-1 present in brain.

Data Analysis: Competition curves were conducted in duplicate, using 10 concentrations of unlabeled drug. Curves were analysed using software from GraphPad Inplot (San Diego, CA). Data were not corrected for the concentration of radioligand since [³H]GABA was employed at a concentration well below its K_d; however, since initial rates were not studied, data are presented as IC₅₀. Data represent means ±SEM.

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RESULTS
Pharmacological characterization of cloned GABA transporters:

In an attempt to identify the GABA transporters in neuronal and glial cell cultures, we adopted a two-pronged strategy: comparison of their pharmacological profiles with those of cloned transporters, coupled with mRNA localization. To avoid possible complications resulting from species differences, we used GAT-1, GAT-2, GAT-3 and TAUT cloned from rat brain, the same species from which the neuronal and glial cell cultures were prepared. As the rat BGT-1 transporter had not yet been cloned, we used PCR to isolate a fragment of it for use in Northern blot analysis of mRNA (see Methods). However, since the full-length clone of rat BGT-1 was not available, we chose to study the pharmacologic properties of a human betaine/GABA transporter (hBGT-1) which we recently cloned from a human brain cDNA library (L.A. Borden, K.E. Smith, E.L. Gustafson, T.A. Branchek, and R.L. Weinshank, manuscript submitted).

In our original description of GAT-2 and GAT-3 (Borden et al., 1992) and TAUT (Smith et al., 1992), we examined inhibitors at limited concentrations. We have now conducted an extensive analysis using 11 drugs which are known inhibitors of GABA and/or taurine transport. Full competition curves were obtained for each drug using 50nM [³H]GABA for the high-affinity GABA transporters (GAT-1, GAT-2, GAT-3, and BGT-1) and 50nM [³H]taurine for TAUT. The results of these studies are summarized in Table 2.

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and AChC, and low affinity for β -alanine. The rank order of potency is NNC-711>nipeptic acid>GABA>hypotaurine> β -alanine>GES>taurine. The pharmacologic profile of GAT-1 is quite dissimilar from that of the other cloned transporters as can be seen from Table 3, which shows the correlation of the pIC₅₀ (-log IC₅₀) values of the various cloned transporters with one another. The most selective GAT-1 compound (NNC-711, 1,000-fold) proved useful in distinguishing GAT-1-mediated GABA transport from that mediated by other GABA transporters in neuronal and glial cultures, and in brain aggregates (see below).

GAT-2 and GAT-3 are pharmacologically similar to one another ($r=0.97$) but distinct from the other cloned transporters (Table 3). In contrast to GAT-1, GAT-2 and GAT-3 have higher affinity for β -alanine than for AChC and NNC-711. The order of potency for GAT-2 is GABA>hypotaurine> β -alanine>(\pm)-nipeptic acid>guvacine>L-DABA>hydroxynipeptic acid>GES>NNC-711>taurine>AChC, while that for GAT-3 is GABA>hypotaurine> β -alanine>(\pm)-nipeptic acid>guvacine>L-DABA>hydroxynipeptic acid>AChC>NNC-711>taurine>AChC. Hypotaurine, a compound classically described as an inhibitor of taurine transporter, is as potent at GAT-2 and GAT-3 as at TAUT.

The pharmacologic profile of hBGT-1 is distinct from that of the other transporters; a modest correlation is observed with GAT-2 and GAT-3 ($r=0.53$ and 0.50, respectively; Table 3). The order of potency is GABA>L-DABA>hypotaurine>AChC> β -alanine>guvacine>(\pm)-nipeptic acid>GES>taurine. Though none of the drugs tested show

Under the conditions employed, GABA shows similar affinity at all four cloned GABA transporters (Table 2). GAT-1 is distinguished by high affinity for NNC-711

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and AChC, and low affinity for β -alanine. The rank order of potency is NNC-711>nipeptic acid>L-DABA>AChC>hypotaurine> β -alanine>GES>taurine. The pharmacologic profile of GAT-1 is quite dissimilar from

that of the other cloned transporters as can be seen from Table 3, which shows the correlation of the pIC₅₀ (-log IC₅₀) values of the various cloned transporters with one another. The most selective GAT-1 compound (NNC-711, 1,000-fold) proved useful in distinguishing GAT-1-mediated GABA transport from that mediated by other GABA transporters in neuronal and glial cultures, and in brain aggregates (see below).

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Under the conditions employed, GABA shows similar affinity at all four cloned GABA transporters (Table 2). GAT-1 is distinguished by high affinity for NNC-711

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selectivity for hBGT-1, a distinguishing feature is the similar potency of β -alanine and AChC.

We also examined the profile of TAUT using [3 H]taurine. The order of potency is hypotaurine>taurine>GES-&math>\beta-alanine>NNC-711>GABA>guvacine>(\pm)-nipecotic acid>hydroxynipecotic acid >AChC>L-DABA. The overall profile correlates poorly with the other transporters (Table 3), though TAUT is similar to GAT-2 and GAT-3 in its preference for β -alanine over AChC. Importantly, the high affinity for taurine distinguishes TAUT from the other transporters.

Preparation of neuronal and glial cell cultures: To examine GABA transport in neurons and astrocytes, we prepared cell cultures highly enriched in each of these cell types (see Methods). Neuronal cultures were established from E17 embryonic brain and were treated with cytosine β -D-arabinofuranoside to inhibit the proliferation of non-neuronal cells (ie., glia and fibroblasts). After one week in vitro the cultures consisted of highly differentiated neurons displaying an intricate network of processes, which stained positively with an anti-neurofilament antibody (Figure 6A).

Raff and colleagues have demonstrated that two classes of astrocytes, designated Type 1 and Type 2, can be identified in cell cultures derived from rat optic nerve (Martin et al., 1989; Raff, 1989). These cell types are morphologically and antigenically distinguishable, and are known to arise from distinct precursors (Lillien and Raff, 1990). Type 1 astrocytes are GFAP-positive, flat, cuboidal cells with a large, oval nucleus. In contrast, Type 2 cells are smaller, stellate cells with an eccentric nucleus and multiple processes (Vaysse and Goldman, 1990; Lillien and Raff, 1990). Type 2 cells are derived from an O-2A precursor

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cell which also gives rise to oligodendrocytes (Raff et al., 1983). Cultures highly enriched in each of these cell types were prepared as described in Methods, and are shown in Figure 6B (Type 1 astrocytes) and Figure 6C (O-2A/Type 2 astrocytes).

Pharmacological characterization of GABA transporter activity in neuronal cell cultures: Neuronal cultures avidly accumulated [3 H]GABA with specific uptake of 42 \pm 4 pmoles per mg protein (n=9). Competition curves using unlabeled GABA were consistent with uptake occurring via a single high-affinity site, IC₅₀ = 10 \pm 2 μ M (n=3). The GAT-1-selective compound NNC-711 was a potent inhibitor (IC₅₀ \approx 300nM) of [3 H]GABA uptake but did not inhibit completely the specific uptake even at high concentrations (Figure 7). When employed at 10 μ M, 31 \pm 1% (n=6) of the specific uptake persisted. This finding indicates that, under these conditions, about 30% of GABA uptake is mediated via a transporter(s) distinct from GAT-1. To characterize these sites we conducted competition curves in both the absence and presence of 10 μ M NNC-711, a concentration sufficient to inhibit transport via GAT-1 almost completely. We used the same 11 drugs used to define the properties of the cloned transporters (Table 2) to allow a direct comparison. As 70% of GABA uptake in neurons is mediated by GAT-1, uptake in the absence of NNC-711 ("NNC-711-sensitive") predominantly reflects transport via this site; in contrast, uptake in the presence of this blocker ("NNC-711-resistant") reflects transport via non-GAT-1 sites. The results of both sets of experiments are shown in Table 4. As expected, GABA transport in the absence of NNC-711 closely resembles the profile of GAT-1: Uptake is sensitive to NNC-711 (see above) and AChC (IC₅₀ \approx 75 μ M), while β -alanine is a weak inhibitor (IC₅₀ \approx 4 mM) (Table 4). The order of potency is NNC-711>GABA>guvacine>(\pm)-nipecotic

acid > hydroxynipeptic acid > ACHC > L-DABA > hypotaurine > GSS > β -alanine > taurine, and the profile correlates well with GAT-1 ($r=0.99$) but poorly with the other transporters (Table 5). These data support the hypothesis that GAT-1 is the predominant GABA transporter in neuronal cultures.

We next examined the affinity of the same drugs in the presence of NNC-711. The affinity of GABA ($IC_{50} = 10\mu M$) is identical to that observed in the absence of NNC-711 (Table 4), consistent with our observation that GABA uptake in the absence of NNC-711 is well described by a single-site model (see above). Interestingly, the NNC-711-resistant GABA transport is more sensitive to β -alanine ($IC_{50} \approx 50\mu M$) than to ACHC ($IC_{50} \approx 2mM$), (Table 3), suggesting that the NNC-711-resistant component is mediated by GAT-2, and/or GAT-3, and/or TAUT. The order of potency is GABA > hypotaurine > β -alanine > (\pm)-nipeptic acid > guvacine > hydroxynipeptic acid > GSS > L-DABA > ACHC > taurine. As shown in Table 5, the highest degree of correlation is with GAT-2 ($r=0.87$) and GAT-3 ($r=0.904$). The correlation with hBGT-1 is modest ($r=0.69$), weaker with GAT-1, and poorest with TAUT. The contribution of these transporters was explored further by Northern blot analysis of neuronal mRNA (see below).

Pharmacological characterization of GABA transporter activity in glial cell cultures: GABA transport was examined separately in Type 1 and O-2A/Type 2 astrocyte cultures. GABA transport in Type 1 cultures was low, averaging only 1.4 ± 0.3 pmoles/mg protein ($n=10$), which is about 3% of the uptake observed in neuronal cultures. The order of potency is guvacine > taurine > hypotaurine > β -alanine > GABA > GES > (\pm)-nipeptic acid > ACHC > hydroxynipeptic acid > GSS > L-DABA (Table 4). The finding that GABA is a weak

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inhibitor ($IC_{50} \approx 300\mu M$) whereas taurine is a potent inhibitor ($IC_{50} \approx 50\mu M$) suggests that GABA uptake in Type 1 astrocytes is mediated by TAUT. Consistent with this idea, the pharmacologic profile correlates most closely with TAUT, although the correlation is only modest ($r=0.52$): a poor correlation is observed with the other transporters (Table 5).

Unlike Type 1 astrocytes, O-2A/Type 2 astrocytes avidly accumulate [³H]GABA (38 ± 4 pmols/mg protein; $n=7$) with high affinity ($IC_{50} \approx 4\mu M$, Table 4). NNC-711 is a potent inhibitor of GABA uptake ($IC_{50} \approx 70\mu M$), but $26 \pm 4\%$ ($n=7$) of the specific uptake persisted in the presence of $10\mu M$ NNC-711 (Figure 7), similar to the situation in neurons. Accordingly, we examined the pharmacological profile of O-2A/Type 2 astrocytes both in the absence and presence of $10\mu M$ NNC-711.

GABA transport in O-2A/Type 2 astrocytes, in the absence of NNC-711, displays high-affinity for NNC-711 ($IC_{50} \approx 70\mu M$) and ACHC ($IC_{50} \approx 35\mu M$), and low-affinity for β -alanine ($IC_{50} \approx 2mM$) (Table 4). The order of potency is NNC-711 > GABA > guvacine > (\pm)-nipeptic acid > hydroxynipeptic acid > ACHC > L-DABA > hypotaurine > β -alanine,

taurine, and there is an excellent correlation with GAT-1 ($r=0.99$, Table 5). Thus, in O-2A/Type 2 astrocytes, as in neurons, the majority of GABA transport is mediated via GAT-1.

GABA transport in O-2A/Type 2 astrocytes in the presence of $10\mu M$ NNC-711 displays high-affinity for GABA ($IC_{50} \approx 2\mu M$) and is more sensitive to β -alanine ($IC_{50} \approx 25\mu M$) than to ACHC ($IC_{50} \approx 2mM$) (Table 4). The order of potency is GABA > β -alanine > hypotaurine > (\pm)-nipeptic acid > guvacine > L-DABA > hydroxynipeptic acid > taurine.

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GES>AHC, and the data correlate best with GAT-2 ($r=0.96$) and GAT-3 ($r=0.94$) (Table 5). The correlation is modest with rBGTR-1 ($r=0.69$), and poor with both GAT-1 and TAUT (<0.25 ; Table 5). To gain further information regarding the contribution of these transporters, we analysed cultures for the presence of transporter mRNA (see below).

Pharmacological characterization of GABA transporter activity in brain aggregates: To examine GABA transport in freshly isolated rat brain, we employed a suspension assay utilizing dissociated brain aggregates. An advantage of this technique is that, unlike purification techniques which yield selective enrichment of various cell types, the brain aggregates include all the cellular elements in the brain in their original proportions:

Rat brain aggregates avidly transport [³H]GABA (83 ± 12 pmoles/mg protein, $n=9$) with high affinity ($IC_{50} \approx 10\mu M$; Table 6). NNC-711 is a potent inhibitor of GABA uptake ($IC_{50} = 90nM$), although $15 \pm 2\%$ ($n=3$) of the uptake persists in the presence of a high concentration ($10\mu M$) of this drug (Figure 8). Accordingly, we examined the pharmacological profile of brain aggregates both in the absence and presence of $10\mu M$ NNC-711.

In the absence of NNC-711, AHC ($IC_{50} = 31\mu M$) is more potent than β -alanine ($IC_{50} \approx 3\mu M$; Table 6). The order of potency is NNC-711 > (\pm)-nipecotic acid > GABA = guvacine = hydroxy nipecotic acid > L-DABA > AHC > hypotaurine > GES > β -alanine > taurine, and there is an excellent correlation with GAT-1 ($r=0.99$) (Table 7). The NNC-711-resistant component of transport has high affinity for β -alanine ($IC_{50} = 33\mu M$) and low affinity for AHC ($IC_{50} \approx 2.5\mu M$). The order of potency is GABA > guvacine > hypotaurine > β -alanine > (\pm)-nipecotic acid > hydroxy nipecotic acid > L-DABA > NNC-

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711 > GES > taurine > AHC (Table 6), and the data correlate best with GAT-2 and GAT-3 ($r=0.96$ and 0.95 , respectively) (Table 7).

Localization of mRNA: We next employed Northern blot analysis to examine the distribution of transporter mRNA in neuronal and glial cultures and in total brain. Probes for GAT-1, GAT-2, GAT-3 and TAUT were labeled to similar specific activities to allow a direct comparison, and Northern blots were reprobed for β B15 (cyclophilin) for the purpose of normalization; however, as only a fragment of rBGTR-1 was available the data obtained with this probe can be compared only semi-quantitatively to the other transporters (see Methods). Representative Northern blots are shown in Figure 10 and the data are quantified in Table 8. As expected from the pharmacology, GAT-1 mRNA is abundant in neurons, whereas Northern blots failed to detect GAT-2 mRNA in neuronal cultures. GAT-3 mRNA is also present in neuronal cultures but the levels are about one third those of neurons. mRNA for rBGTR-1 is not detected by densitometry in neuronal cultures, though visual inspection of the autoradiograms sometimes reveals the presence of a faint band. TAUT mRNA is present at levels about 1.5-fold higher than GAT-1.

In Type 1 astrocyte cultures, mRNAs for GAT-1, GAT-2, and GAT-3 are not detectable by Northern blot analysis (Figure 10 and Table 8). In contrast, mRNAs for rBGTR-1 and TAUT are fairly abundant.

Levels of transporter mRNA expression in O-2A/Type 2 astrocytes are more variable than in the other cell types. GAT-1 mRNA was abundant in these cultures (Figure 10, Table 8), with levels approximately half those in neurons. GAT-2 mRNA is the most abundant GABA transporter with levels approximately 4-fold greater than GAT-1 mRNA. GAT-3 mRNA is present at levels about

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half those of GAT-1. mRNA for rGBT-1 and TAUT are also present in O-2A/Type 2 astrocytes, at levels similar to that of GAT-1. Thus, O-2A/Type 2 cultures contain all the known GABA transporters.

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In summary, GAT-1 mRNA is present in neurons and O-2A/Type 2 astrocytes, as is GAT-3. GAT-2 mRNA is present in O-2A/Type 2 astrocytes, but not in neurons or Type 1 astrocytes. Type 1 astrocytes also lack GAT-1 and GAT-3. rGBT-1 mRNA is present in Type 1 and O-2A/Type 2 astrocyte cultures, but is rarely observed in neurons, and then at low levels. TAUT mRNA is present in all cell types examined, with the highest abundance in Type 1 astrocytes.

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Using poly A' RNA from total rat brain, all four high-affinity GABA transporters, and TAUT, were detected by Northern blots (not shown). GAT-1 and GAT-3 mRNAs were both quite abundant, while the levels of GAT-2 mRNA were about 20% of GAT-1 (Table 8). In contrast, BGT-1 and TAUT mRNA were relatively scarce, with levels $\approx 10\%$ those of GAT-1 mRNA (Table 8).

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Table 2. Pharmacological profile of cloned GABA and taurine transporters. Data show the IC₅₀ (in μ M) for inhibition of [³H]GABA uptake (GAT-1, GAT-2, rGBT-1, or [³H]taurine uptake (TAUT) at the indicated cloned transporters. Values represent means \pm SEM of at least three experiments.

Clone/ drug	IC ₅₀ , μ M			
	rGAT-1	rGAT-2	r-GAT-3	rGBT-1
GABA	30 \pm 8	17 \pm 6	33 \pm 10	42 \pm 12
ACHC	132 \pm 44	25,900 \pm 12,600	55,100 \pm 25,000	1,070 \pm 508
guava- cine	39 \pm 6	228 \pm 38	378 \pm 18	1,420 \pm 201
hydrox- Y- nipecot- ic	44 \pm 8	567 \pm 50	467 \pm 53	3,840 \pm 688
(+)- nipecot- ic acid	24 \pm 6	113 \pm 33	159 \pm 30	2,350 \pm 253
NNC-771	0.38 \pm 0.07	129 \pm 319	349 \pm 151	3,570 \pm 1,140
hypotau- rine	1,010 \pm 13	52 \pm 6	73 \pm 7	536 \pm 41
β - alanine	2,920 \pm 197	66 \pm 9	110 \pm 40	1,100 \pm 66
GES	4,840 \pm 1,200	698 \pm 110	915 \pm 49	4,800 \pm 910
L-DABA	128 \pm 12	3000 \pm 51	710 \pm 237	528 \pm 62
taurine	32,300 \pm 12,000	1,270 \pm 40	2,860 \pm 358	13,200 \pm 1250

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Table 3. Correlation of GABA transport activity of cloned transporters. The pIC₅₀ values for inhibition of [³H]GABA uptake (GAT-1, GAT-2, GAT-3, hBGT-1) or [³H]taurine uptake (TAUT) at each of the cloned transporters was correlated with the values at the other transporters (data from Table 2). Data represent r values.

clone	rGAT-1	rGAT-2	rGAT-3	hBGT-1
rGAT-2	-0.07			
rGAT-3	0.22	0.97		
hBGT-1	0.27	0.53	0.50	
TAUT	-0.41	0.26	0.28	-0.26

Table 4. Pharmacological profile of GABA transport in rat neurons and gliial cell cultures. Data show the IC₅₀ (in nM) for inhibition of [³H]GABA uptake in neurons and gliial cultures, in the absence and presence of NNC-711. Values represent means ± SEM of at least three experiments.

assay condition/ drug	Neurons	Neurons with NNC- 711	Type 1 astrocyte s	Type 2 astrocyte s	O-2A/ type 2 astrocytes with NNC- 711	IC ₅₀ , nM
GABA	10±2	10±1	294±100	4±0.2	2±0.4	
ACHC	77±8	1,950±	400±200	35±4	2,360±	
GUVACHE	14±2	136±45	23±10	8±0.9	81±30	
hydroxy-acid	22±2	304±10	1,610±	17±3	197±20	
(+)-nitroacetoc acid	18±5	119±20	315±100	12±2	61±20	
NNC-711	0.28±0.1	ND ²	2±0.3	0.07±	ND	
hypotaurine	742±200	25±2	69±30	62±2	29±15	
B-alanine	4,060±	48±10	100±30	2,030±	24±8	
GES	0,110±60	508±60	310±60	1,560±	603±300	

TABLE 4 (CONTINUED)

L-DABA	165±20	861±22 5	3,460± 2,000	74±10	91±30
taurine	8,300± 3,000	2,490± 900	47±10	13,000± 6,000	328±200

¹ determined in the presence of 10μM NNC-711² not determined

Table 5. Correlation of GABA transport activity in neuronal and astrocyte cultures with cloned GABA and taurine transporters. The pIC₅₀ values for inhibition of [³H]GABA transport in neuronal and astrocyte cultures (from Table 4) were correlated with the pIC₅₀ values at each of the cloned transporters (data from Table 2). Data represent r values.

clone/assay condition	GAT-1	GAT-2	GAT-3	HBGT-1	TAUT
neurons	0.99	0.04	0.19	0.20	-0.35
neurons with NNC-711	0.36	0.87	0.90	0.69	0.24
Type 1 astrocytes	0.29	-0.12	-0.02	-0.16	0.52
O-2A/Type 2 astrocytes	0.99	0.07	0.22	0.30	-0.35
O-2A/Type 2 astrocytes with NNC-711	0.24	0.96	0.94	0.69	0.25

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Table 6. Pharmacological Profile of GABA transport in rat brain aggregates. Data show the IC₅₀ (in μ M) for inhibition of [³H]GABA uptake. Values represent means \pm SEM of at least three experiments.

	IC ₅₀ , μ M
assay condition/ drug	control with NNC- 711 ¹
GABA	10 \pm 2
ACHC	31 \pm 4
guvacine	10 \pm 2
hydroxy- nipecotic acid	10 \pm 1
(\pm)- nipecotic acid	7 \pm 0.8
NNC-711	0.09 \pm 0.01
hypotaurine	692 \pm 100
β -alanine	2,930 \pm 500
GES	1,340 \pm 100
L-DABA	22 \pm 3
taurine	67,000 \pm 20,000

¹ determined in the presence of 10 μ M NNC-711

Table 7. Correlation of GABA transport activity in rat brain aggregates with cloned GABA and taurine transporter. The pIC₅₀ values for inhibition of GABA transport in brain aggregates (data from Table 6) were correlated with the pIC₅₀ values at each of the cloned transporters (data from Table 2). Data represent r values.

clone/assay condition	GAT-1	GAT-2	GAT-3	hBGT-3	TAUT
control	0.99	0.03	0.18	0.28	-0.50
10 μ M NNC-711	0.13	0.96	0.95	0.63	0.13

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Table 8. Quantitation of GABA transporter mRNA localization. Autoradiograms of Northern blots (such as those shown in Figure 10) were quantitated by densitometry, then corrected for the amount of mRNA as determined by hybridization to the constitutive mRNA encoding cyclophilin. Data are expressed as a fraction of GAT-1 mRNA present in neuronal cultures (for cell cultures), or total brain. Data for neurons, Type 1 astrocytes, and O-2A/Type 2 astrocytes are means of 3 or 4 independent platings, assayed on separate gels.

cell culture/ clone	Neurons	Type 1 astrocytes	O- 2A/Type 2 astrocyt- es	brain
GAT-1 ¹	1 ¹	0	0.4	1 ¹
GAT-2	0	0	1.7	0.2
GAT-3	0.3	0	0.2	1.2 ¹
BGT-1 ²	0	0.6	0.3	0.1
TAUT	1.6	2.2	0.6	0.1

DISCUSSION

The application of molecular biology to the study of GABA transporters has provided considerable insight into this important class of synaptic proteins, but has also raised a number of questions. For example, it has not been clear which transporters are expressed in neurons and which in glia, nor what role each plays in regulating synaptic transmission. Particularly confusing is the apparent lack of correspondence between the newly cloned transporters and the classically described glial transport systems (see Introduction). In an attempt to resolve these issues we have combined pharmacological studies with mRNA localization, employing primary cultures of neurons, and Type 1 and O-2A/Type 2 astrocytes. The results for each of these cell types will be discussed individually.

As expected from earlier studies, the majority of GABA transport activity in neuronal cultures has the properties of GAT-1, most notably high affinity for NNC-711 and AchC, and low affinity for β -alanine. Consistent with these pharmacological results, we found that GAT-1 mRNA was abundant in neuronal cultures. These results are also consistent with *in situ* hybridization studies which demonstrate that GAT-1 mRNA is abundant in many GABAergic neurons in the rat brain (Rattray and Priestley, 1993; M.M. Durkin, E.L. Gustafson, K.E. Smith, L.A. Borden, P.R. Hartig, R.I. Weinshank, and T.A. Branchek, manuscript submitted).

¹ By definition

²The specific activity of the rat BGT-1 probe was lower than that of the other probes (see Methods), thus the data underestimate the actual abundance

Interestingly, we observed that in neuronal cultures approximately 30% of GABA uptake is mediated by a non-GAT-1 mechanism, a finding not recognized by earlier investigators. The pharmacologic profile of this activity correlated well with GAT-2 and GAT-3, whose

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profiles are similar. However, Northern blot analysis revealed the presence in these cultures of mRNA for GAT-3 but not GAT-2, suggesting that GAT-3 mediates the uptake. The correlation with BGT-1 ($r = 0.687$) was only slightly better than the correlation between GAT-3 and BGT-1 (0.503), suggesting that rBGT-1 makes only a minor contribution to the observed GABA transport. Consistent with this hypothesis, rBGT-1 mRNA was either absent, or present at very low levels in neuronal cultures. A role for GAT-3 in neuronal cultures is consistent with *in situ* hybridization studies which demonstrate that GAT-3 mRNA is present in rat brain neurons (Clark et al., 1992; M.M. Durkin, E.L. Gustafson, K.E. Smith, L.A. Borden, P.R. Hartig, R.L. Weinshank, and T.A. Branchek, unpublished observations), though it is less abundant than GAT-1. Taken together, these data indicate clearly that neuronal GABA transport is heterogeneous, though it is not yet known whether both GABA transporters are expressed in individual neurons.

In contrast to neurons, Type 1 astrocytes transport only low levels of GABA and the transport is sensitive to β -alanine, in agreement with earlier autoradiographic studies (Reynolds and Herschkowitz, 1984). However, we found that the transport activity had low affinity for GABA and high affinity for taurine, suggesting that uptake is mediated by TAUT. It is interesting that we have recently observed similar results with a variety of glial cell lines (L.A. Borden, unpublished observations). Northern blots of Type 1 astrocytes demonstrated the presence of mRNA for TAUT and rBGT-1, but the absence of mRNA for GAT-1, GAT-2, and GAT-3. GABA transport activity correlated best with TAUT, though the correlation was only modest ($r = 0.523$). There was essentially no correlation with BGT-1, despite the relative abundance of rBGT-1 mRNA.

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This discrepancy might reflect pharmacologic differences between rat and human BGT-1, as we have observed between human, mouse, and dog BGT-1 (L.A. Borden, K.E. Smith, E.L. Gustafson, T.A. Branchek, and R.L. Weinshank, unpublished observations); confirmation of this issue must await cloning of a full length cDNA for rBGT-1. Alternatively, we cannot rule out the existence in Type 1 astrocytes of an as-yet uncloned transporter. None-the-less, the low level of [3 H]GABA transport in Type 1 astrocytes, and the low affinity for GABA, suggest that BGT-1 makes little contribution to GABA transport in these cells, despite the presence of rBGT-1 mRNA. It is possible that this discrepancy is an artifact of cell culture and that BGT-1 is expressed at high levels *in vivo*. A similar phenomenon has been reported in GH3 cells which have been shown to produce mRNA for the dopamine D₂ receptor, although receptor binding is not detectable (Missale et al., 1991).

GABA transport in O-2A/Type 2 astrocytes differed considerably from that in Type 1 astrocytes, as expected from earlier autoradiographical studies. Previous investigations of GABA transport in astrocytes of the O-2A/Type 2 revealed these cells to have a "neuronal-like" pharmacology, based on their sensitivity to AChC and insensitivity to β -alanine (Levi et al., 1983; Reynolds and Herschkowitz, 1984; Johnstone et al., 1986). However, precise interpretation of these data was complicated by the use of single concentrations of inhibitor and the qualitative nature of the assay (Reynolds and Herschkowitz, 1984; Johnstone et al., 1986), or the use of mixed astrocyte cultures (Levi et al., 1983). Our combined pharmacological and mRNA analyses establish unequivocally not only that GAT-1 is present in O-2A/Type 2 astrocyte cultures but that it is abundant in these cells, as it is in neurons. These results are in

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agreement with those of Mabjeesh et al. (1992) who observed GAT-1-like immunoreactivity in cultured astrocytes with an O-2A/Type 2 morphology. Importantly, the data are also consistent with those of Radian et al. (1990), who observed GAT-1 immunoreactivity in glial processes in sections of rat brain.

We also observed that approximately 25% of GABA transport in O-2A/Type 2 astrocytes was resistant to NNC-711 and was thus mediated by a transporter distinct from GAT-1. The pharmacological profile correlated best with GAT-2 and GAT-3, and Northern blots revealed the presence in these cells of mRNA for both of these transporters. The levels of GAT-2 mRNA were greater than those for GAT-1, whereas GAT-3 mRNA was present at lower levels. Thus, despite quantitative differences, there is qualitative agreement between the pharmacology and mRNA localization. mRNA for rBGT-1 was also fairly abundant though the correlation with hBGT-1 ($r=0.685$) was only slightly greater than would be expected were the transport activity mediated solely by GAT-2 and/or GAT-3 (see Table 3). Taken together, the data suggest that the NNC-711-resistant uptake in O-2A/Type 2 astrocytes is mediated primarily by GAT-2 though GAT-3 and to a lesser extent rBGT-1, may also contribute. It is interesting to note that O-2A/Type 2 astrocytes exhibit the greatest heterogeneity in expression of GABA transporters, with all five present.

In brain aggregates, 85% of GABA uptake has a GAT-1-like pharmacology and GAT-1 mRNA is abundant. mRNA for GAT-2, GAT-3, and BGT-1 are all present though surprisingly, these transporters together account for approximately 15% of total GABA transport, thus suggesting a mismatch between protein and mRNA levels.

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Previous autoradiographic studies in which brain slices were incubated with [3 H]GABA suggested that glial cells make only a minor contribution to overall GABA uptake in vivo (Iversen and Bloom, 1972; Martin, 1972). This is consistent with our finding of low GABA uptake in Type 1 astrocytes but is in contrast to O-2A/Type 2 astrocytes, which avidly accumulate GABA. However, it has been suggested (Marriott and Wilkin, 1993) that Type 2 astrocytes correspond to reactive astrocytes which proliferate in response to brain injury, but which are rare in the normal (i.e., non-injured) brain. A similar situation has been demonstrated for nerve growth factor mRNA which is not present in adult glia, but whose expression is high during development and following injury, as well as in actively growing astrocytes *in vitro* (Lu et al., 1991). The hypothesis that glial cells make only a minor contribution to GABA uptake *in vivo* is supported by *in situ* hybridization studies of transporter mRNAs which reveal little (M.M. Durkin, E.L. Gustafson, K.E. Smith, L.A. Borden, P.R. Hartig, R.L. Weinshank, and T.A. Brancheck, unpublished observations) or no labeling in glial cells (Rattray and Priestley, 1993; Clark et al., 1992), despite heavy labeling in many populations of neurons. It is possible that GABA transporter mRNAs are present in glial cells but at low copy numbers, which are below the limits of detection by *in situ* PCR. Amplification of the signal by *in situ* PCR may be required to visualize these transporters in glial cells. Alternatively, the apparent absence of GABA transporter mRNA in glial cells may be a technical problem relating to the small size of glial cells, since silver grains are more readily observed in large cells. It is clear that further experiments are required to resolve this critical issue.

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Numerous animal studies (reviewed in Krogsgaard-Larsen et al., 1987) and more recently, clinical studies with human patients (Chadwick et al., 1991), indicate that inhibitors of GABA transport possess anti-convulsive activity, presumably by increasing GABAergic transmission. It has been argued that glial transporters are the preferred target since inhibition of neuronal transport would be expected to result in depletion of GABA in the nerve terminal; the net effect of this depletion would be an eventual decrease in GABAergic transmission (Krogsgaard-Larsen et al., 1987). However, the findings that 1. GAT-1 is not restricted to neurons; 2. neuronal transport appears to predominate over glial transport; and 3. β -alanine-sensitive transporters are observed in neurons, as well as glia, suggest a re-evaluation of the role of neuronal and glial transporters in the treatment of convulsive disorders. It should be emphasized that the presence of GAT-1 in neurons and glia precludes the development of a glial- (or neuronal) selective drug directed towards this site.

In conclusion, we have utilized a combined pharmacological and molecular biological approach to re-examine GABA transport in neuronal and glial cell cultures. The salient points of these studies may be summarized as follows: 1. GAT-1 mRNA is present in both neurons and O-2A/Type 2 astrocytes, and appears to account for the majority of GABA transport in both cell types; 2. GAT-3 mRNA is observed in neurons and O-2A/Type 2 astrocytes, though at levels below those of GAT-1 or GAT-2; 3. GAT-2 mRNA is present in O-2A/Type 2 cells, but is not detectable (by Northern blots) in neurons; 4. Type 1 astrocytes exhibit very low levels of GABA transport, and this activity has low affinity for GABA but high affinity for taurine. mRNAs for TAUT and BGT-1 are present in these cultures, whereas those

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for GAT-1, GAT-2 and GAT-3 are not detected. 5. the pharmacologic data in glial cells can be explained by the presence of various combinations of the known cloned transporters, and no evidence was obtained for the existence of the classical "glial transporter". These findings provide new insight into the regulation of GABAergic transmission in the central nervous system and should aid in the development of novel therapeutic agents acting at GABA transporters.

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Determination of Tiagabine, SKF 89976-A, CI-966, and RNC-711 Selectivity for the Cloned GABA Transporters GAT-1, GAT-2, GAT-3 and hGAT-1.

GAT-1, GAT-2, GAT-3 and hGAT-1.
Y-Aminobutyric acid (GABA) is the major inhibitory neurotransmitter in the mammalian central nervous system. Drugs that modulate GABAergic activity, such as the benzodiazepines and barbiturates, are efficacious in the treatment of a variety of neuro-psychiatric disorders, in particular epilepsy and anxiety (Twyman and Macdonald, 1991; Goodchild, 1991).

Following its release into the synapse, GABA is rapidly transported into presynaptic terminals and surrounding astroglial cells by high-affinity, sodium-dependent transporters; this process aids in the termination of GABA action and also prevents the spread of neurotransmitter, thereby assuring the fidelity of neurotransmission (for reviews see Krogsgaard-Larsen et al., 1987; Kanner and Schuldiner, 1987). Pharmacologic inhibition of uptake provides a novel mechanism for sustaining levels of neurotransmitter in the synapse and thereby increasing synaptic transmission.

Determining the efficacy of GABA transport inhibitors such as nipeptic acid *in vivo* has been hampered by their poor penetration of the blood-brain barrier, a property attributable to their high degree of hydrophobicity. In an effort to overcome this problem, Ali et al. (1985) examined the effect of adding lipophilic side chains to the nitrogen atom of various GABA transport blockers. Surprisingly, the addition of 4,4-diphenyl-3-butetyl side chains to nipeptic acid and guvacine (SK&F 89976-A and SK&F 100330-A, respectively) resulted in a 120-fold increase in potency, when tested in brain synaptosomes. Since the original report, a number of other groups have synthesized similar derivatives such as CI-966 (Bjorge

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et al., 1990) and tiagabine (Andersen et al., 1993). Importantly, these compounds all display anticonvulsive activity in laboratory animals (Yunger et al., 1984; Swinyard et al., 1991; Nielsen et al., 1991; Taylor et al., 1990; Suzdak et al., 1992).

Determining the site of action of the lipophilic GABA transport inhibitors is essential to understanding their mechanism of action, but is complicated by the heterogeneity of GABA transport. Early studies with cell culture systems suggested the existence of distinct neuronal and glial GABA transport systems (reviewed in Krogsgaard-Larsen et al., 1987). More recently, molecular cloning has identified four distinct GABA transporters termed GAT-1 (Guastella et al., 1990), GAT-2 (Borden et al., 1992), GAT-3 (Borden et al., 1992), and GAT-4, the latter transporting both GABA and the osmolyte betaine (Yamauchi et al., 1992). A clone identical to GAT-3 was described by Clark et al. (1992) and termed GAT-B. Clones for all four GABA transporters have been identified in mice (Liu et al., 1993), though a different terminology was employed: mouse GAT-1 is the homologue of rat GAT-1; mouse GAT-2 is the homologue of GAT-1; mouse GAT-3 is the homologue of rat GAT-2; and mouse GAT-4 is the homologue of rat GAT-3.

In the present report, we have examined the potency of four lipophilic transport inhibitors at each of the four cloned GABA transporters. We find that they all show a high degree of selectivity for GAT-1, indicating that their anticonvulsive activity is mediated via inhibition of GABA transport by this site. This information should be useful in understanding the role of GABA in brain function and in the design of novel transport inhibitors.

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2. MATERIAL AND METHODS

2.1 Materials

[³H]GABA (98.9Ci/mmol) was obtained from New England Nuclear (Boston, MA). GABA was from Sigma Chemical Corporation (St. Louis, MO); (R,S)-nipeptic acid, guvacine, and NNC-711 were from Research Biochemical Incorporated (Natick, MA). CI-966 (Bjorge et al., 1990) and SKF-89976-A (Ali et al., 1985) were synthesized as described previously. Tiagabine was synthesized as described by Andersen et al. (1993).

2.2 Methods

2.2.1 Stable transfection: stable cell lines for human GAT-1, rat GAT-2, human GAT-3, and human BGT-1 were generated in LM(tk) cells using the calcium phosphate method and selection in G-418, as described previously (Weinshank et al., 1992). Cells were grown under standard conditions (37°C, 5% CO₂) in DMEM (Dulbecco's modified Eagle's medium; GIBCO, Grand Island, NY). Human GAT-1 is the human homologue of the rat transporter GAT-1 (Nelson et al., 1990) which we recloned. Human GAT-3 and human BGT-1 are the human homologues of rat GAT-3 (Borden et al., 1992) and dog BGT-1 (Yamauchi et al., 1992); a more complete description of these homologues will be described in subsequent communications (Borden et al., in preparation).

2.2.2 Transient transfection: GABA transport by rat GAT-1 and rat GAT-3 was examined in transiently transfected cells. Transient transfections were conducted as previously described (Smith et al., 1992), with the following modifications: COS cells grown in 75 cm² or 150 cm² flasks in DMEM with 10% bovine calf serum, 100 U/ml penicillin G, and 100 µg/ml streptomycin sulfate (37°C, 5%CO₂) were transfected using DEAE-dextran. On the day following transfection the cells were split into 24-well assay plates (well

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diameter = 18 mm) coated with poly-D-lysine (10 µg/ml), and transport was measured 24 hours later.

2.2.3 Transport assay: Transport by attached cells was measured as described previously (Borden et al., 1992), with the following modifications. Cells grown in 24-well plates were washed 3X with HEPES-buffered saline (HBS, in mM: NaCl, 150; HEPES, 20; CaCl₂, 1; glucose, 10; KCl, 5; MgCl₂, 1; pH 7.4) and allowed to equilibrate on a 37°C slide warmer. After 10 minutes the medium was removed and unlabeled drugs in HBS were added (450 µl/well). Transport was initiated by adding 50 µl per well of a concentrated solution of [³H]GABA in HBS (final concentration = 50 nM). Non-specific uptake was defined in parallel wells with 1 mM unlabeled GABA, and was subtracted from total uptake (no competitor) to yield specific uptake; all data represent specific uptake. Plates were incubated at 37°C for 10 minutes, then washed rapidly 3X with ice-cold HBS, using a 24-position plate washer (Brandel, Gaithersburg, MD; model PW-12). Cells were solubilized with 0.05% sodium deoxycholate/0.1N NaOH (0.25 ml/well), an aliquot neutralized with 1N HCl, and radioactivity was determined by scintillation counting. Protein was quantified in an aliquot of the solubilized cells using a BIO-RAD protein assay kit, according to the manufacturer's directions.

Lipophilic inhibitors were dissolved in methylsulfoxide (DMSO). The final concentration of DMSO in the transport assay was ≤2%, and control experiments demonstrated that this concentration had no significant effect on transport.

2.2.4 Data Analysis: Competition curves were conducted in duplicate, using 10 concentrations of unlabeled drug. IC₅₀ values (concentrations resulting in 50% inhibition of uptake) were derived using software from

GraphPad Inplot (San Diego, CA). Data were not corrected for the concentration of radioligand since [³H]GABA was employed at a concentration well below its K_d; however, since initial rates were not studied, data are presented as IC₅₀. All data throughout the paper represent means ± S.E.M.

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GraphPad Inplot (San Diego, CA). Data were not corrected for the concentration of radioligand since [³H]GABA was employed at a concentration well below its

K_d; however, since initial rates were not studied, data are presented as IC₅₀. All data throughout the paper represent means ± S.E.M.

3. RESULTS

In the present study we used transfected cell lines expressing rat and human GAT-1; rat GAT-2, rat and human GAT-3, and human BGT-1. Fig. 11 shows a dendrogram describing the amino acid relationships between these transporters. As described previously (Borden et al., 1992), GAT-2 and GAT-3 are more closely related to each other than to GAT-1. Human BGT-1 is most related to GAT-2, and least to GAT-1. As expected, species homologues are highly related to one another.

Fig. 12 shows the structures of the lipophilic compounds examined in this study, as well as the parent compounds (\pm -)nipeptic acid and guvacine. SK&F 89976-A (N-(4,4-diphenyl-3-butenyl)-3-piperidinecarboxylic acid) is a nipeptic derivative with a 4,4-diphenyl-3-butenyl moiety attached to the ring nitrogen (Yunger et al., 1984). Triagabine ((R)-1-(4,4-Bis(3-methyl-2-thienyl)-3-butenyl)-3-piperidinecarboxylic acid) is similar to SK&F 89976-A but has a bis-3-methylthienyl substituent instead of the two phenyl groups (Andersen et al., 1993). CR-966 (1-[2-[bis(4-(trifluoromethyl)phenyl)methoxy]ethyl]-1,2,5,6-tetrahydro-3-pyridinecarboxylic acid) is a guvacine derivative and differs from the previous two compounds, in having a para-substituted trifluoromethyl biphenyl ether moiety attached to the ring nitrogen via an ethylene bridge (Bjorge et al., 1990). NNC-711 (1-(2-((diphenylmethylene)amino)oxy)ethyl)-1,2,4,6-tetrahydro-3-pyridinecarboxylic acid hydrochloride) is also a guvacine derivative with a biphenylmethyleneoxime unit attached to the ring nitrogen, also via an ethylene bridge (Suzdak et al., 1992).

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1992).

Table 9 shows the potency of GABA and the hydrophilic inhibitors nipecotic acid, guvacine, and β -alanine at each of the four cloned GABA transporters. GABA displays similar high-affinity ($IC_{50} \approx 5 \mu M$) at human GAT-1, rat GAT-2, and human GAT-3, but is approximately 7-fold less potent at human BGT-1. The lower affinity of GABA at rat GAT-1 and rat GAT-3 is due, at least in part, to the use of transient transfection for these clones (L. Borden, unpublished) and perhaps to species differences in transporter structure that may alter drug affinities. Table 9 also shows that (t)-nipecotic acid and guvacine display modest selectivity for GAT-1 (IC_{50} s = 14-39 μM) as compared to GAT-2 and GAT-3 (IC_{50} s = 102-378 μM), whereas both compounds have low affinity at hBGT-1 ($IC_{50} > 1 mM$). (R)-nipecotic acid is more potent than (S)-nipecotic acid, and accounts for most of the activity of the racemate. As described previously (Borden et al., 1992), β -alanine has greater potency at GAT-2 and GAT-3 (IC_{50} s = 19-110 μM) than at GAT-1, regardless of species; β -alanine also displays low potency ($IC_{50} > 1 mM$) at hBGT-1.

The data for the potency of the lipophilic compounds at the cloned transporters are summarized in Table 9, and a representative experiment for Tiagabine is shown in Fig. 13. The IC_{50} values of the lipophilic compounds at GAT-1 range between 26 and 260nM at GAT-1 (Table 9); these compounds are thus 50- to 200-fold more potent at this transporter than are (t)-nipecotic acid and guvacine. The compound with the highest affinity at human GAT-1 is NNC-711, followed by Tiagabine, SKF 89976-A, and CI-966. A similar order of potency is observed at rat GAT-1 although the absolute affinities are somewhat lower.

In contrast to GAT-1, the lipophilic compounds all display low affinity at GAT-2, GAT-3, and BGT-1. As

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shown in Table 9, the IC_{50} values at these transporters range from about 300 μM to greater than 1 mM, regardless of species (rat or human) or type of transfectant (stable or transient). Thus, all four lipophilic compounds display specificity for GAT-1 of nearly three orders of magnitude when compared to the other cloned GABA transporters. These findings confirm and extend the report by Clark et al. (1992) that NNC-711 has higher affinity for GAT-1 than GAT-3.

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Table 9. Affinity of transport inhibitors at cloned GABA transporters.

The compounds shown were examined for their ability to inhibit uptake of [³H]GABA by each of the cloned GABA transporters, as described in Methods. Data show the IC₅₀ for inhibition of [³H]GABA uptake, in μ M, and represent means \pm S.E.M.; the values in parentheses indicate the number of experiments.

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IC₅₀, μ M

clone/ compound	human GAT-1	rat GAT-1	rat GAT-2	human GAT-3	rat GAT-3	human BGT-1
GABA	5 \pm 1 (3)	30 \pm 8 (3)	5 \pm 2 (3)	7 \pm 1 (4)	33 \pm 10 (3)	36 \pm 3 (4)
(R,S)-nipecotic acid	8 \pm 0.4 (3)	24 \pm 6 (3)	38 \pm 4 (4)	106 \pm 13 (3)	159 \pm 30 (3)	2370 \pm 617 (4)
(R)-nipecotic acid	5.96 \pm 0.8 (3)	ND*	19 \pm 2 (3)	51 \pm 6 (4)	ND	2310 \pm 114 (3)
(S)-nipecotic acid	116 \pm 8 (3)	ND	763 \pm 55 (3)	2320 \pm 86 (4)	ND	6410 \pm 213 (3)
guvacine	14 \pm 3 (3)	39 \pm 6 (3)	58 \pm 5 (4)	119 \pm 24 (3)	378 \pm 175 (3)	1870 \pm 387 (3)
β -alanine	5690 \pm 1890 (3)	2920 \pm 197 (3)	19 \pm 7 (3)	58 \pm 3 (3)	110 \pm 40 (3)	1320 \pm 224 (3)
CI-966	0.26 \pm 0.05 (4)	1.2 \pm 0.2 (5)	297 \pm 34 (3)	333 \pm 76 (3)	1140 \pm 337 (3)	300 \pm 10 (3)
Tiagabine	0.07 \pm 0.007 (7)	0.64 \pm 0.15 (5)	1410 \pm 250 (3)	917 \pm 193 (3)	2040 \pm 107 (3)	1670 \pm 722 (3)
SK&F 89976-A	0.13 \pm 0.01 (3)	0.64 \pm 0.19 (5)	550 \pm 225 (4)	944 \pm 259 (3)	4390 \pm 1420 (3)	7210 \pm 3630 (4)

TABLE 9 (CONTINUED)

NNC-711	0.04 \pm 0.01 (4)	0.38 \pm 73 (4)	171 \pm 53 (5)	1700 \pm 252 (3)	349 \pm 151 (3)	622 \pm 265 (4)
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*ND not determined

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4. DISCUSSION

Molecular cloning has revealed a surprising diversity of GABA transporters. However, little is known regarding the relative contribution of the four cloned GABA transporters to GABAergic transmission. The lipophilic compounds SK&F 89976-A, Tiagabine, CI-966, and NNC-711 all display anticonvulsive activity in animals (Yunger et al., 1984; Swinyard et al., 1991; Nielsen et al., 1991; Taylor et al., 1990; Suzdak et al., 1992). Further, Tiagabine has demonstrated anti-seizure activity in patients in Phase II clinical trials (Richens et al., 1992; Crawford et al., 1993; Rowan et al., 1993), thus demonstrating the therapeutic utility of inhibiting GABA transport. Our finding that these compounds are highly selective for GAT-1 demonstrates clearly that their anticonvulsive activity is mediated via actions at this site. It should be noted that GAT-1 is the predominant GABA transporter in the rat brain, accounting for approximately 85% of GABA transport when assayed *in vitro* (Borden et al., submitted).

Severe adverse effects were noted in human volunteers after administration of CI-966 (Sedman et al., 1990), but were not observed with Tiagabine (Richens et al., 1992; Rowan et al., 1993; Crawford et al., 1993). The finding that both compounds display a similar selectivity at the cloned GABA transporters suggests a common site of action in the brain. The untoward side-effects of CI-966 may have resulted from the high doses employed in the trials; alternatively, they may reflect interactions of either the parent compound, or a toxic metabolite, with sites distinct from GABA transporters (for further discussion, see Suzdak, 1993).

Due to their high degree of selectivity for GAT-1, the lipophilic compounds described above are important tools for the study of this transporter but offer little insight into the functions of the other cloned GABA transporters; future experiments will be aimed at the development of lipophilic ligands for these sites. Further study of the lipophilic GABA transport inhibitors should increase our understanding of GABA transporters and the role they play in regulating GABAergic activity, and may result in the development of novel therapeutic agents for anxiety, epilepsy, and other neuropsychiatric disorders.

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TTT CTG AAC CAC TCA GGA GCC ACC GTG ACC CCA TTT GAG AAT TTT
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 ATC CTC ACC ATC GCC GTC ATG TGC TAC CTC CTC ATA GGG CTC TTC CTG GTC
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 480
 ATT GGC TAC CGG CCA TGG CCC CGC CGT RAG ATC TCC TGG CTC TTC CTG
 1722 Ile Gly Tyr Arg Pro Trp Pro Leu Val Lys Ile Ser Trp Leu Phe Leu
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 560
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 1952 Leu Arg Gln Leu Ile Thr Pro Asp Ser Ser Leu Pro Glu Pro Lys Glu
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 CAT CCC TGC TTG GAT GCC ACT CCT GGC CGG AAC TTT GGG CCC TCC CCA
 2010

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H10 Pro Cys Leu Asp Gly Ser Ala Gly Arg Asn Phe Gly Pro Ser Pro
585 590
ACA AGG GAA CGA CTG ATA GCC GCG GAG AAG ACC CAT TRG
2052 2057
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2112 2172
CATTCCTAGG GGACAGGCTC TGGCTCTGTC TCTGGCACA ATCCCTCTGG GAACTCTGG
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2217 2272

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2217 2272

(2) INFORMATION FOR SEQ ID NO:2:

(i) SEQUENCE CHARACTERISTICS:

- (A) LENGTH: 614 amino acids
- (B) TYPE: amino acid
- (D) TOPOLOGY: linear

(ii) MOLECULE TYPE: protein

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:2:

Met Asp Gly Val Ala Val Glu Tyr Gly Pro Pro Ala Val Ser
1 5 10 15
Trp Val Pro Glu Glu Gly Leu Asp Gln Glu Asp Gln
20 25 30
Val Lys Asp Arg Gly Gln Trp Thr Asn Lys Met Gln Phe Val Leu Ser
35 40 45
Val Ala Gly Glu Ile Ile Gly Leu Gly Asn Val Trp Arg Phe Pro Tyr
50 55 60
Leu Cys Tyr Lys Asn Gly Gly Ala Phe Phe Ile Pro Tyr Phe Ile
65 70 75
Phe Phe Val Cys Gly Ile Pro Val Phe Phe Leu Glu Val Ala Leu
85 90 95
Gly Gln Tyr Thr Ser Gln Gly Ser Val Thr Ala Trp Arg Lys Ile Cys
100 105 110
Pro Leu Phe Gln Gly Ile Gly Leu Ala Ser Val Val Ile Glu Ser Tyr
115 120 125
Leu Asn Val Tyr Tyr Ile Ile Ile Leu Ala Trp Ala Leu Phe Tyr Leu
130 135 140
Phe Ser Ser Phe Thr Ser Ser Glu Leu Pro Trp Thr Cys Asn Asn Phe
145 150 155
Trp Asn Thr Glu His Cys Thr Asp Phe Leu Asn His Ser Gly Ala Gly
165 170 175
Thr Val Thr Pro Phe Glu Asn Phe Thr Ser Pro Val Met Glu Phe Trp
185 190
Glu Arg Arg Val Leu Gly Ile Thr Ser Gly Ile His Asp Leu Gly Ser
195 200 205

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Leu Arg Trp Glu Leu Ala Leu Cys Leu Leu Asn Trp Val Val Ile Cys
210 215
Tyr Phe Cys Ile Trp Lys Gly Val Lys Ser Thr Gly Lys Val Val Tyr
225 230 235
Phe Thr Ala Thr Phe Pro Tyr Leu Met Leu Ile Leu Ile Arg
245 250 255
Gly Val Thr Leu Pro Gly Ala Tyr Glu Gly Ile Ile Tyr Tyr Leu Lys
265 270
Pro Asp Leu Phe Arg Leu Lys Asp Pro Glu Val Trp Met Asp Ala Gly
280 285
Thr Gln Ile Phe Phe Ser Phe Ala Ile Cys Gln Gly Cys Leu Thr Ala
290 295 300
Leu Gly Ser Tyr Asn Lys Tyr His Asn Asn Cys Tyr Lys Asp Cys Ile
310 315 320
Ala Leu Cys Phe Leu Asn Ser Ala Thr Ser Phe Val Ala Gly Phe Val
330 335 340
Ser Gln Val Ala Glu Ser Gly Pro Gly Leu Ala Phe Ile Ala Phe Pro
360 365 370
Val Phe Ser Ile Leu Gly Phe Met Ser Gln Glu Gln Gly Val Pro Ile
375 380 385
Lys Ala Val Thr Met Met Pro Leu Ser Gln Leu Ser Cys Leu Phe
390 395 400
Phe Ile Met Leu Ile Phe Leu Gly Leu Asp Ser Gln Phe Val Cys Val
405 410 415
Lys Ser Gly Arg Arg Glu Leu Leu Ile Leu Thr Ile Ala Val Met Cys
420 425 430
Glu Cys Leu Val Thr Ala Ser Ile Asp Met Phe Pro Arg Gln Leu Arg
435 440 445
Tyr Leu Ile Gly Leu Phe Leu Val Thr Glu Gly Met Tyr Ile Phe
450 455 460
Gln Leu Phe Asp Tyr Tyr Ala Ser Ser Gln Ile Cys Leu Leu Phe Leu
465 470 475
Ser Leu Phe Glu Val Val Cys Ile Ser Trp Val Tyr Gly Ala Asp Arg
480 485 490
Phe Tyr Asp Asn Ile Glu Asp Met Ile Gly Tyr Arg Pro Trp Pro Leu
500 505 515
Val Lys Ile Ser Trp Leu Phe Leu Thr Pro Gln Leu Cys Leu Ala Thr
520 525 530
Tyr Val Tyr Pro Pro Trp Gly Tyr Ser Ile Gly Trp Phe Leu Ala Leu
540 545 550
Ser Ser Met Val Cys Val Pro Leu Phe Val Val Ile Thr Leu Leu Lys
555 560

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Thr Arg Gly Pro Phe Arg Lys Arg Leu Ile Thr Pro Asp
565 570 575

Ser Ser Leu Pro Gln Pro Lys Cln His Pro Cys Leu Asp Gly Ser Ala
580 585 590 595

Gly Arg Asn Phe Glu Pro Ser Pro Thr Arg Glu Gly Ile Ala Gly
600 605

Glu Lys Glu Thr His Leu
610

(2) INFORMATION FOR SEQ ID NO:3:

- (1) SEQUENCE CHARACTERISTICS:
 - (A) LENGTH: 45 base pairs
 - (B) TYPE: nucleic acid
 - (C) STRANDEDNESS: single
 - (D) TOPOLOGY: linear

(11) MOLECULE TYPE: cDNA

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:3:

GTCCTGAAGA TCTCAGATCC CATCAGACM CTGGGCTCC CGCC

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(2) INFORMATION FOR SEQ ID NO:4:

- (1) SEQUENCE CHARACTERISTICS:
 - (A) LENGTH: 45 base pairs
 - (B) TYPE: nucleic acid
 - (C) STRANDEDNESS: single
 - (D) TOPOLOGY: linear

(11) MOLECULE TYPE: cDNA

(iv) ANTI-SENSE: YES

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:4:

45

CGAGGAGCCA CAGGACCAAGG TCCTCACCGA CGGACCCCG AGCGT

(2) INFORMATION FOR SEQ ID NO:5:

- (1) SEQUENCE CHARACTERISTICS:
 - (A) LENGTH: 423 base pairs
 - (B) TYPE: nucleic acid
 - (C) STRANDEDNESS: single
 - (D) TOPOLOGY: linear

(11) MOLECULE TYPE: cDNA

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:5:

CCCATTAAGCT GTGGTATCCC ACTGTCTTC CTGCAAGCTG CACTGGTCA CTATACAGGC
60
CAAGGGAGCT TTRACTGCTG GAGGAGATC TGTCAAGCTC TCAAGGCC ATGCCATGG
120
TCGTGCTCA TCCAGCTTTA TTGGACATC TACTACATCA TCACTCTTC CGGGCTTC
180
TTCTACCTGT TCAGGCTCTI CACCTGGAG CTTCCTGGAA CAACCTGCAC CAACTCTGG
240
AACACAGAAC ATGGGTTGA CTTCTGAAC TACCTCTGA CCAAGCCGC AAGCTACT
300

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GAGACATCA CCTCACAGGT CATGGATTC TGGGAGAC GCCTTTCGG TATTACATCA
360
GGCATCCATG ACCTGGGTG CCTGGCCTGC GAGCTGGCC TGTGCTCTCT GTCGGCTGG
420
ATC
423

(2) INFORMATION FOR SEQ ID NO:6:

(1) SEQUENCE CHARACTERISTICS:

- (xi) SEQUENCE DESCRIPTION: SEQ ID NO:6:
- (1) LENGTH: 139 amino acids
- (B) TYPE: amino acid
- (D) TOPOLOGY: linear

(11) MOLECULE TYPE: protein

Ser Cys Gly Ile Pro Val Phe Leu Glu Val Ala Leu Gly Glu Tyr
5 10 15
Ser Ser Gln Gly Ser Val Thr Ala Trp Arg Lys Ile Cys Pro Leu Leu
20 25
Gln Gly Ile Gly Met Ala Ser Val Val Ile Glu Ser Tyr Leu Arg Ile
35 40 45
Tyr Tyr Ile Ile Leu Ala Trp Ala Leu Phe Tyr Leu Phe Ser Ser
50 55
Phe Thr Trp Glu Lau Pro Trp Thr Thr Cys Thr Asn Ser Trp Asn Thr
55 60 65
Glu His Cys Val Asp Phe Leu Asn Tyr Ser Ser Thr Arg Ala Ala Ser
85 90 95
Tyr Ser Glu Asn Phe Thr Ser Pro Val Met Glu Phe Trp Glu Arg Arg
100 105 110
Val Leu Gly Ile Thr Ser Gly Ile His Asp Leu Gly Ser Leu Arg Trp
115 120 125
Glu Leu Ala Leu Cys Ile Leu Ala Trp Ile
130 135

(2) INFORMATION FOR SEQ ID NO:7:

(1) SEQUENCE CHARACTERISTICS:

- (xi) SEQUENCE DESCRIPTION: SEQ ID NO:7:
- (1) LENGTH: 614 amino acids
- (B) TYPE: amino acid
- (D) TOPOLOGY: linear

(11) MOLECULE TYPE: protein

His Asp Arg Lys Val Ala Val His Glu Asp Gly Tyr Pro Val Val Ser
1 5 10 15
Trp Val Pro Glu Glu Gly Ile Glu Met Met Asp Gln Iys Gly Lys Asp Gln
20 25
Val Lys Asp Arg Gly Glu Trp Thr Asn Lys Met Glu Phe Val Leu Ser
35 40 45

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Val Ala Gly Glu Ile Ile Gly Leu Gly Asn Val Trp Arg Phe Pro Tyr
 50 55 60
 Leu Cys Tyr Lys Asn Gly Gly Ala Phe Phe Ile Pro Tyr Phe Ile
 65 70 75 80
 Phe Phe Ser Cys Gly Ile Pro Val Phe Phe Leu Glu Val Ala Leu
 85 90 95
 Gly Cln Tyr Ser Ser Cln Gly Ser Val Thr Ala Trp Arg Lys Ile Cys
 100 105 110
 Pro Leu Cln Gly Ile Gly Met Ala Ser Val Val Ile Glu Ser Tyr
 115 120 125
 Leu Asn Ile Tyr Tyr Ile Ile Leu Ala Trp Ala Leu Phe Tyr Leu
 130 135 140
 Phe Ser Ser Phe Thr Trp Glu Leu Pro Trp Thr Thr Cys Thr Asn Ser
 145 150 155 160
 Trp Asn Thr Glu His Cys Val Asp Phe Leu Asn His Ser Ser Ala Arg
 165 170 175
 Gly Val Ser Ser Ser Cln Asn Phe Thr Ser Pro Val Met Gln Phe Trp
 180 185 190
 Glu Arg Arg Val Leu Gly Ile Thr Ser Gly Ile His Asp Leu Gly Ser
 195 200 205
 Leu Arg Trp Glu Leu Ala Leu Cys Leu Leu Ala Trp Ile Ile Cys
 210 215 220
 Tyr Phe Cys Ile Trp Lys Gly Val Lys Ser Thr Gly Lys Val Val Tyr
 225 230 235 240
 Phe Thr Ala Thr Phe Pro Tyr Leu Met Leu Ile Leu Leu Ile Arg
 245 250 255
 Gly Val Thr Leu Pro Gly Ala Tyr Gln Gly Ile Val Phe Tyr Leu Lys
 260 265 270
 Pro Asp Leu Arg Leu Lys Asp Pro Gln Val Trp Met Asp Ala Gly
 275 280
 Thr Cln Ile Phe Phe Ser Phe Ala Ile Cys Gln Gly Cys Leu Thr Ala
 290 295 300
 Lys Gly Ser Tyr Asn Lys Asn Asn Cys Tyr Arg Asp Ser Ile
 305 310 315
 Ala Leu Cys Phe Leu Asn Ser Ala Thr Ser Phe Val Ala Gly Phe Val
 325 330 335
 Asx Phe Ser Ile Leu Gly Phe Met Ser Gln Gln Gly Ile Pro Ile
 340 345 350
 Ser Glu Val Ala Glu Ser Cys Pro Gly Leu Ala Phe Ile Ala Phe Pro
 355 360
 Lys Ala Val Thr Met Met Pro Leu Ser Gln Leu Trp Ser Cys Leu Phe
 370 375 380
 Phe Ile Met Leu Leu Phe Leu Gly Leu Asp Ser Gln Phe Val Cys Met
 385 390 395
 400

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Glu Cys Leu Val Thr Ala Ser Met Asp Met Phe Pro Gln Gln Leu Arg
 405 410 415
 Lys Ser Gly Arg Arg Asp Val Leu Ala Ile Ser Val Leu Cys
 420 425
 Tyr Leu Met Gly Leu Leu Val Thr Ala Gly Gly Met Tyr Ile Phe
 435 440 445
 Gln Leu Phe Asp Tyr Tyr Ala Ser Ser Gly Ile Cys Leu Leu Phe Leu
 450 455
 Ser Leu Phe Glu Val Ile Cys Ile Gly Trp Val Tyr Gly Ala Asp Arg
 465 470 475 480
 Phe Tyr Asp Asn Val Glu Asp Met Ile Gly Tyr Arg Pro Trp Pro Leu
 485 490 495
 Val Lys Ile Ser Trp Leu Phe Leu Thr Pro Gly Leu Cys Leu Ala Thr
 500 505 510
 Phe Phe Ser Leu Ser Lys Tyr Tyr Pro Leu Lys Tyr Asn Asn Val
 515 520 525
 Tyr Met Tyr Pro Ser Trp Gly Tyr Ser Ile Gly Trp Leu Leu Ala Phe
 530 535 540
 Ser Ser Met Ala Cys Val Pro Leu Phe Ile Ile Thr Phe Leu Lys
 545 550 555 560
 Thr Gln Gly Ser Phe Lys Lys Arg Leu Arg Arg Leu Ile Thr Pro Asp
 555 560 565 570 575
 Pro Ser Leu Pro Gln Pro Gly Arg Pro Trp Gln Asp Gly Ser Ser
 580 585 590 595
 Ala Gln Asn Cys Ser Ser Pro Ala Lys Gln Glu Leu Ile Ala Trp
 600 605 610
 Glu Lys Glu Thr His Leu

(2) INFORMATION FOR SEQ ID NO:8:

(1) SEQUENCE CHARACTERISTICS:

- (A) LENGTH: 614 amino acids
- (B) TYPE: amino acid
- (C) TOPOLOGY: linear

(11) MOLECULE TYPE: protein

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:8:

Met Asp Arg Lys Val Ala Val Pro Gln Asp Gly Pro Pro Val Val Ser
 1 5 10 15
 Trp Leu Pro Gln Glu Gly Glu Lys Leu Asp Gln Glu Asp Gln
 20 25 30
 Val Lys Asp Arg Gly Gln Trp Thr Alan Lys Met Glu Phe Val Leu Ser
 35 40 45
 Val Ala Gly Glu Ile Ile Gly Leu Gly Asn Val Trp Arg Phe Pro Tyr
 50 55 60

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Leu Cys Tyr Lys Asn Cys Gly Gly Ala Phe Ile Pro Tyr Phe Ile
 65 70 75 80 85 90 95 100 105 110 115 120 125 130 135 140 145 150 155 160
 Phe Phe Thr Cys Gly Ile Pro Val Phe Phe Leu Glu Val Ala Leu
 Gly Glu Tyr Thr Ser Gin Gly Ser Val Thr Ala Trp Arg Lys Ile Cys
 Pro Leu Leu Cln Gly Ile Gly Leu Ala Ser Val Val Ile Glu Ser Tyr
 Leu Asn Ile Tyr Tyr Ile Ile Ile Leu Ala Trp Ala Leu Phe Tyr Leu
 Trp Asn Thr Glu His Cys Met Asp Phe Leu Asn His Ser Cys Ala Arg
 Thr Ala Thr Ser Ser Glu Asn Phe Thr Ser Pro Val Asn Glu Phe Trp
 Glu Arg Val Leu Gly Ile Thr Ser Gly Ile His Asp Leu Gly Ala
 Leu Arg Trp Glu Leu Ala Leu Leu Leu Ala Trp Leu Ile Cys
 Tyr Phe Cys Ile Trp Lys Gly Val Lys Thr Thr Cys Val Val Tyr
 Phe Thr Ala Thr Phe Pro Tyr Leu Met Leu Val Ile Leu Ile Arg
 Gly Ile Thr Leu Pro Gly Ala Tyr Glu Gly Val Ile Tyr Tyr Leu Lys
 Pro Asp Leu Leu Arg Leu Lys Asp Pro Gln Val Trp Asn Asp Ala Gly
 Thr Cln Ile Phe Phe Ser Phe Ala Ile Cys Gln Gly Cys Leu Thr Ala
 Leu Gly Ser Tyr Asn Lys Tyr His Asn Asn Cys Tyr Arg Asp Ser Ile
 Ala Leu Cys Phe Leu Asn Ser Ala Thr Ser Phe Ala Ala Gly Phe Val
 Val Phe Ser Ile Leu Gly Phe Met Ala Gln Gln Gly Leu Pro Ile
 Ser Glu Val Ala Glu Ser Gly Pro Gly Leu Ala Phe Ile Ala Phe
 Lys Ala Val Thr Met Met Pro Leu Ser Gln Leu Trp Ser Cys Leu Phe
 Phe Ile Met Leu Ile Phe Leu Gly Leu Asp Ser Cys Gln Phe Val Cys Val
 Glu Cys Leu Val Thr Ala Ser Met Asp Met Phe Pro Ser Gln Leu Arg

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Lys Ser Gly Arg Glu Leu Leu Ile Leu Ala Ile Asn Val Phe Cys
 Tyr Leu Ala Gly Leu Phe Leu Val Thr Glu Gly Met Tyr Ile Phe
 Ala Met Phe Glu Val Ile Cys Ile Ser Trp Val Tyr Gly Ala Asp Arg
 Phe Tyr Asp Asn Ile Glu Asp Met Ile Gly Tyr Arg Pro Trp Pro Leu
 Val Lys Ile Ser Trp Leu Phe Leu Thr Pro Gly Leu Cys Leu Ala Thr
 Tyr Val Tyr Pro Pro Trp Gly Tyr Ser Ile Gly Trp Phs Leu Ala Leu
 Ser Ser Met Ile Cys Val Pro Leu Lys Tyr Asn Asn Ile
 Thr Arg Gly Ser Phe Lys Lys Arg Leu Arg Gln Leu Thr Thr Pro Asp
 Pro Ser Leu Pro Gln Pro Lys Gln His Leu Tyr Leu Asp Gly Gly Thr
 Ser Gln Asp Cys Gly Pro Ser Pro Thr Lys Glu Gly Leu Ile Val Gly

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Lys Ser Gly Arg Glu Leu Leu Ile Leu Ala Ile Asn Val Phe Cys
 Tyr Leu Ala Gly Leu Phe Leu Val Thr Glu Gly Met Tyr Ile Phe
 Ala Met Phe Glu Val Ile Cys Ile Ser Trp Val Tyr Gly Ala Asp Arg
 Phe Tyr Asp Asn Ile Glu Asp Met Ile Gly Tyr Arg Pro Trp Pro Leu
 Val Lys Ile Ser Trp Leu Phe Leu Thr Pro Gly Leu Cys Leu Ala Thr
 Tyr Val Tyr Pro Pro Trp Gly Tyr Ser Ile Gly Trp Phs Leu Ala Leu
 Ser Ser Met Ile Cys Val Pro Leu Lys Tyr Asn Asn Ile
 Thr Arg Gly Ser Phe Lys Lys Arg Leu Arg Gln Leu Thr Thr Pro Asp
 Pro Ser Leu Pro Gln Pro Lys Gln His Leu Tyr Leu Asp Gly Gly Thr
 Ser Gln Asp Cys Gly Pro Ser Pro Thr Lys Glu Gly Leu Ile Val Gly

(2) INFORMATION FOR SEQ ID NO:9:

(i) SEQUENCE CHARACTERISTICS:
 (A) LENGTH: 602 amino acids
 (B) TYPE: amino acid
 (D) TOPOLOGY: linear

(ii) MOLECULE TYPE: protein

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:9:

Met Asp Asn Arg Val Ser Gly Thr Ser Asn Gly Glu Thr Lys Pro
 1 5 10 15
 Val Cys Pro Val Met Glu Lys Val Glu Asp Gly Thr Leu Glu Arg
 20 25 30
 Glu Glu Trp Thr Asn Lys Met Glu Phe Val Leu Ser Val Ala Gly Glu
 35 40
 Ile Ile Gly Leu Gly Asn Val Trp Arg Phe Pro Tyr Leu Cys Tyr Lys
 50 55 60
 Asn Gly Gly Gly Ala Phe Glu Ile Pro Tyr Leu Ile Phe Leu Phe Thr

65 70 75 80
 405 410 415
 405 410 415

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Cys Gly Ile Pro Val Phe Phe Leu Glu Thr Ala Leu Gly Cln Tyr Thr
85 90
Asn Gln Gly Ile Thr Ala Trp Arg Lys Ile Cys Pro Ile Phe Glu
100 105
Gly Ile Gly Tyr Ala Ser Gln Met Ile Val Ser Leu Leu Asn Val Tyr
115 120
Tyr Ile Val Val Ala Leu Phe Tyr Leu Phe Ser Ser Phe
130 135
Thr Thr Asp Leu Pro Trp Gly Ser Cys Ser His Glu Trp Asn Thr Glu
145 150 160
Asn Cys Val Glu Phe Gln Lys Thr Asn Asn Ser Leu Asn Val Thr Ser
165 170
Glu Asn Ala Thr Ser Pro Val Ile Glu Phe Trp Glu Arg Val Leu
180 185
Lys Ile Ser Asp Gly Ile Gln His Leu Gly Ser Leu Leu Arg Trp Glu Leu
195 200
Val Leu Cys Leu Leu Ala Trp Ile Ile Cys Tyr Phe Cys Ile Trp
210 215 220
Lys Gly Val Lys Ser Thr Gly Lys Val Val Tyr Phe Thr Ala Thr Phe
225 230 235
Pro Tyr Leu Met Leu Val Val Leu Ile Arg Gly Val Thr Leu Pro
245 250 255
Gly Ala Ala Gln Gly Ile Gln Phe Tyr Leu Tyr Pro Asn Ile Thr Arg
260 265 270
Leu Trp Asp Pro Gln Val Trp Asn Asp Ala Gly Thr Gln Ile Phe Phe
275 280 285
Ser Phe Ala Ile Cys Leu Gly Cys Leu Thr Ala Leu Gly Ser Tyr Asn
290 295 300
Lys Tyr His Asn Asn Cys Tyr Arg Asp Cys Val Ala Leu Cys Ile Leu
305 310 315
Asn Ser Ser Thr Ser Phe Val Ala Gly Phe Ala Ile Phe Ser Ile Leu
325 330 335
Gly Phe Asn Ser Gln Gln Gly Val Pro Ile Ser Gln Val Ala Glu
340 345 350
Ser Gly Pro Gly Leu Ala Phe Ile Ala Tyr Pro Arg Ala Val Val Asn
355 360 365
Leu Pro Phe Ser Pro Leu Trp Ala Cys Cys Phe Phe Asn Val Val
370 375 380
Leu Leu Gly Leu Asp Ser Gln Phe Val Cys Val Glu Ser Leu Val Thr
385 390 395
Ala Leu Val Asp Asn Tyr Pro Arg Val Phe Arg Lys Asn Arg Arg
405 410 415
Glu Ile Leu Ile Leu Ile Val Ser Val Val Ser Phe Ile Gly Leu
420 425 430

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Ile Met Leu Thr Glu Gly Gly Asn Tyr Val Phe Gln Leu Phe Asp Tyr
435 440
Tyr Ala Ala Ser Gly Met Cys Leu Leu Phe Val Ala Ile Phe Glu Ser
450 455 460
Leu Cys Val Ala Trp Val Tyr Gly Ala Ser Arg Phe Tyr Asp Asn Ile
465 470 475 480
Glu Asp Met Ile Gly Tyr Lys Pro Trp Pro Leu Ile Lys Tyr Cys Trp
485 490 495
Leu Phe Phe Thr Pro Ala Val Cys Leu Ala Thr Phe Leu Phe Ser Leu
500 505 510
Ile Lys Tyr Thr Pro Leu Thr Tyr Asn Lys Lys Tyr Thr Tyr Pro Trp
515 520 525
Trp Gly Asp Ala Leu Gly Trp Leu Leu Ala Leu Ser Ser Met Val Cys
530 535 540
Ile Pro Ala Trp Ser Ile Tyr Lys Leu Arg Thr Leu Lys Gly Pro Leu
545 550 555 560
Arg Glu Arg Leu Arg Gln Leu Val Cys Pro Ala Glu Asp Leu Pro Gln
565 570 575
Lys Ser Gln Pro Glu Leu Thr Ser Pro Ala Thr Pro Met Thr Ser Leu
585 590
Leu Arg Leu Thr Glu Leu Glu Ser Asn Cys
595 600

(2) INFORMATION FOR SEQ ID NO:10

- (i) SEQUENCE CHARACTERISTICS:
- (A) LENGTH: 627 amino acids
- (B) TYPE: amino acid
- (D) TOPOLOGY: linear

(iii) MOLECULE TYPE: protein

(xi) SEQUENCE DESCRIPTION: SEQ ID NO:10
Met Thr Ala Glu Gln Ala Leu Pro Leu Gly Asn Gly Lys Ala Ala Glu
1 5
Glu Ala Arg Gly Ser Gln Ala Leu Gly Gly Gly Gly Gly Ala Ala
20 25 30
Gly Thr Arg Glu Ala Arg Asp Lys Ala Val His Glu Arg Gly His Trp
35 40
Asn Asn Lys Val Glu Phe Val Val Ala Gly Glu Ile Ile Gly
50
Leu Gly Asn Val Trp Arg Phe Pro Tyr Leu Cys Tyr Lys Asn Gly Gly
65 70 75 80
Gly Ala Phe Leu Ile Pro Tyr Val Val Phe Phe Ile Cys Cys Gly Ile
85 90 95
Pro Val Phe Phe Leu Glu Thr Ala Leu Gln Phe Thr Ser Glu Gly
100 105

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Gly Ile Thr Cys Trp Arg Arg Val Cys Pro Leu Phe Glu Gly Ile Gly
115 120 125 130 135 140 145 150 155 160 165 170 175 180 185 190 195 200 205 210 215 220 225 230 235 240 245 250 255 260 265 270 275 280 285 290 295 300 305 310 315 320 325 330 335 340 345 350 355 360 365 370 375 380 385 390 395 400 405 410 415 420 425 430 435 440 445 450 455 460 465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000

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Ala Ala Ser Gly Met Cys Ile Leu Phe Val Ala Ile Phe Glu Cys Val
465 470 475 480 485 490 495 500 505 510 515 520 525 530 535 540 545 550 555 560 565 570 575 580 585 590 595 600 605 610 615 620 625 630 635 640 645 650 655 660 665 670 675 680 685 690 695 700 705 710 715 720 725 730 735 740 745 750 755 760 765 770 775 780 785 790 795 800 805 810 815 820 825 830 835 840 845 850 855 860 865 870 875 880 885 890 895 900 905 910 915 920 925 930 935 940 945 950 955 960 965 970 975 980 985 990 995 1000

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What is claimed is:

1. An isolated nucleic molecule encoding a mammalian betaine\GABA transporter.
 5. 2. A nucleic acid molecule of claim 1, wherein the nucleic acid molecule encodes a human betaine\GABA transporter.
 10. 3. A nucleic acid molecule of claim 1, wherein the nucleic acid molecule is a DNA molecule.
 15. 4. A DNA molecule of claim 3, wherein the DNA molecule is a cDNA molecule.
 20. 5. A DNA molecule of claim 3, wherein the DNA molecule is derived from genomic DNA.
 25. 6. A nucleic acid molecule of claim 2, wherein the nucleic acid molecule is a DNA molecule.
 30. 7. A vector comprising a DNA molecule of claim 3.
 8. A plasmid vector of claim 7.
 35. 9. An expression vector of claim 7 adapted for expression in a bacterial cell which comprises the regulatory elements necessary for expression of the DNA encoding a betaine\GABA transporter in the bacterial cell operatively linked to the cDNA encoding the betaine\GABA transporter as to permit expression thereof.
 10. An expression vector of claim 7 adapted for expression in a yeast cell which comprises the regulatory elements necessary for the expression of the DNA encoding a betaine\GABA transporter in the yeast cell operatively linked to the cDNA encoding a betaine\GABA transporter as to permit expression thereof.
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5. 11. An expression vector of claim 7 adapted for expression in a mammalian cell which comprises the regulatory elements necessary for expression of the DNA encoding a betaine\GABA transporter in the mammalian cell operatively linked to the cDNA encoding a betaine\GABA transporter as to permit expression thereof.
 10. 12. A plasmid of claim 8 adapted for expression in a mammalian cell which comprises the regulatory elements necessary for expression of the DNA in the mammalian cell operatively linked to the DNA encoding a betaine\GABA transporter to permit expression thereof.
 15. 13. A plasmid of claim 16 designated pcEXV-hBGT (ATCC).
Accession No. 75393).
 20. 14. A mammalian cell comprising the plasmid of claim 10.
 25. 15. A mammalian cell of claim 14, wherein the mammalian cell is an LM (tk-) cell.
 30. 16. A mammalian cell of claim 14, wherein the mammalian cell is a COS7 cell.
 35. 17. An LM (tk-) cell comprising the plasmid of claim 13 designated L-BGT (ATCC Accession No. CRL11229).
 18. A nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a

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unique sequence included within the sequence of a nucleic acid molecule encoding a mammalian betaine/GABA transporter.

5 19. A nucleic acid probe comprising a nucleic acid molecule of at least 15 nucleotides capable of specifically hybridizing with a unique sequence included within the sequence of a nucleic acid molecule encoding a human betaine/GABA transporter.

10 20. The nucleic acid probe of claim 18, wherein the nucleic acid is DNA.

15 21. A mixture of nucleic acid probes in accordance with claim 18, such probes having sequences which differ from one another at predefined positions.

20 22. An antisense oligonucleotide having a sequence capable of specifically binding to a mRNA molecule encoding a mammalian betaine/GABA transporter so as to prevent translation of the mRNA molecule.

25 23. An antisense oligonucleotide capable of specifically binding to a mRNA molecule encoding a human betaine/GABA transporter so as to prevent translation of the mRNA molecule.

30 24. An antisense oligonucleotide of claim 22 comprising chemical analogs of nucleotides.

35 25. A mixture of antisense oligonucleotides according to claim 22, such oligonucleotides having sequences which differ from one another at predefined positions.

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26. A method for detecting expression of a mammalian betaine/GABA transporter, which comprises obtaining RNA from cells or tissue, contacting the RNA so obtained with a nucleic acid probe of claim 18 under hybridizing conditions, detecting the presence of any mRNA hybridized to the probe, the presence of mRNA hybridized to the probe indicating expression of the mammalian betaine/GABA transporter, and thereby detecting the expression of the mammalian betaine/GABA transporter.

5 27. A method for detecting expression of a human betaine/GABA transporter, which comprises obtaining RNA from cells or tissue, contacting the RNA so obtained with a nucleic acid probe of claim 19 under hybridizing conditions, detecting the presence of any mRNA hybridized to the probe, the presence of mRNA hybridized to the probe indicating expression of the human betaine/GABA transporter, and thereby detecting the expression of the human betaine/GABA transporter.

10 28. A method of detecting expression of a mammalian betaine/GABA transporter in a cell or tissue by *in situ* hybridization, which comprises contacting the cell or tissue with a nucleic acid probe of claim 18 under hybridizing conditions, detecting the presence of any mRNA hybridized to the probe, the presence of mRNA hybridized to the probe indicating expression of a mammalian betaine/GABA transporter, and thereby detecting the expression of a mammalian betaine/GABA transporter.

15 29. A method of detecting expression of a human betaine/GABA transporter in a cell or tissue by *in situ* hybridization, which comprises contacting the

cell or tissue with a nucleic acid probe of claim 19 under hybridizing conditions, detecting the presence of any mRNA hybridized to the probe, the presence of mRNA hybridized to the probe indicating expression of a human betaine/GABA transporter, and thereby detecting the expression of the human betaine/GABA transporter.

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30. A method of isolating from a gene library a gene encoding a transporter which comprises contacting the library under hybridizing conditions with a probe of claim 20 and isolating any gene to which the probe hybridizes.

10 31. A method of claim 30, which additionally comprises simultaneously contacting the DNA comprising the library under hybridizing conditions with a second nucleic acid probe comprising a sequence capable of hybridizing to a DNA sequence of the complementary strand of the DNA of the gene to which the first probe hybridizes, treating any gene sequence to which both probes hybridized so as to produce multiple copies of the gene sequence, isolating the amplified gene sequence and using the isolated gene sequence as a probe to isolate from a gene library the gene to which the amplified DNA sequence hybridizes.

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34.. A synthetic gene which comprises the isolated nucleic acid molecule of claim 1 and at least one regulatory element attached thereto so as to decrease the number of RNA molecules transcribed from the synthetic gene.

5 35. An isolated mammalian betaine/GABA transporter protein.

10 36. The transporter protein of claim 35, wherein the mammalian betaine/GABA transporter protein is a human betaine/GABA transporter.

15 37. A method of preparing a mammalian betaine/GABA transporter of claim 35, which comprises inducing cells to express the mammalian betaine/GABA transporter and recovering the mammalian betaine/GABA transporter from the resulting cells.

20 38. A method of preparing a mammalian betaine/GABA transporter protein of claim 35, which comprises inserting a nucleic acid molecule encoding the mammalian betaine/GABA transporter in a suitable vector, inserting the resulting vector in suitable host cell and recovering the mammalian betaine/GABA transporter produced by the resulting cell.

25 39. A method of preparing a human betaine/GABA transporter of claim 36, which comprises inducing cells to express the human betaine/GABA transporter and recovering the human betaine/GABA transporter from the resulting cells.

30 40. A method of preparing a human betaine/GABA transporter protein of claim 36, which

35

from the synthetic gene.

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comprises inserting a nucleic acid molecule encoding the human betaine/GABA transporter in a suitable vector, inserting the resulting vector in suitable host cell and recovering the human betaine/GABA transporter produced by the resulting cell.

41. An antibody directed to a mammalian betaine/GABA transporter or to a protein fragment of the mammalian betaine/GABA transporter.

42. An antibody directed to a human betaine/GABA transporter or to a protein fragment of the human betaine/GABA transporter.

43. An antibody of claim 41, wherein the antibody is a monoclonal antibody.

44. An antibody of claim 42, wherein the antibody is a monoclonal antibody.

45. A monoclonal antibody of claim 43, wherein the antibody is directed to an epitope of a mammalian cell-surface betaine/GABA transporter and having an amino acid sequence substantially the same as the amino acid sequence of a cell-surface epitope of the mammalian betaine/GABA transporter.

46. A monoclonal antibody of claim 44, wherein the antibody is directed to an epitope of a human cell-surface betaine/GABA transporter and having an amino acid sequence substantially the same as the amino acid sequence for a cell-surface epitope of the human betaine/GABA transporter.

47. A pharmaceutical composition comprising an amount of a substance effective to alleviate the

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abnormalities resulting from overexpression of a human betaine/GABA transporter and a pharmaceutically acceptable carrier.

5. 48. A pharmaceutical composition comprising an amount of a substance effective to alleviate abnormalities resulting from underexpression of a human betaine/GABA transporter and a pharmaceutically acceptable carrier.

10. 49. A pharmaceutical composition comprising an effective amount of an oligonucleotide of claim 23 effective to reduce expression of a human betaine/GABA transporter by passing through a cell membrane and specifically binding with mRNA encoding a human betaine/GABA transporter in the cell so as to prevent its translation and a pharmaceutically acceptable hydrophobic carrier capable of passing through a cell membrane.

20. 50. A pharmaceutical composition of claim 49, wherein the nucleotide is coupled to a substance which inactivates mRNA.

15. 51. A pharmaceutical composition of claim 50, wherein the substance which inactivates the mRNA is a ribozyme.

30. 52. A pharmaceutical composition of claim 50, wherein the pharmaceutically acceptable hydrophobic carrier capable of passing through a cell membrane comprises a structure which binds to a transporter specific for a selected cell type and is thereby taken up by the cells of the selected cell type.

35. 53. A pharmaceutical composition which comprises an amount of the antibody of claim 42 effective to

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block binding of naturally occurring substrates to a human betaine/GABA transporter and a pharmaceutically acceptable carrier.

5. 54. A transgenic nonhuman mammal which comprises a nucleic acid molecule of claim 1.
5. 55. A transgenic nonhuman mammal whose genome comprises a nucleic acid molecule of claim 1 so placed as to be transcribed into antisense mRNA complementary to mRNA encoding a human betaine/GABA transporter and which hybridizes to mRNA encoding a human betaine/GABA transporter thereby reducing its translation.
10. 56. The transgenic nonhuman mammal of claim 54, wherein the nucleic acid molecule further comprises an inducible promoter.
15. 57. The transgenic nonhuman mammal of claim 54 or 56 wherein the nucleic molecule additionally comprises tissue specific regulatory elements.
20. 58. The transgenic non-human mammal of 54 wherein the transgenic non-human mammal is a mouse.
25. 59. A method for determining the physiological effects of varying the levels of expression of a human betaine/GABA transporter which comprises producing a transgenic non-human mammal whose levels of expression of a human betaine/GABA transporter can be varied by use of an inducible promoter.
30. 60. A method for determining the physiological effects of expressing varying levels of a human betaine/GABA transporter which comprises producing a panel of transgenic non-human mammals each
5. 61. A method for determining whether a compound not known to be capable of specifically binding to a human betaine/GABA transporter can specifically bind to the human betaine/GABA transporter, which comprises contacting a mammalian cell comprising a plasmid adapted for expression in a mammalian cell which plasmid further comprises a DNA which expresses a human betaine/GABA transporter on the cell's surface with the compound under conditions permitting binding of ligands known to bind to a human betaine/GABA transporter, detecting the presence of any compound bound to the human betaine/GABA transporter, the presence of bound compound indicating that the compound is capable of specifically binding to the human betaine/GABA transporter.
10. 62. The method of claim 61, wherein the mammalian cell is a non-neuronal cell.
15. 63. A method of screening compounds to identify drugs which interact with, and specifically bind to, a human betaine/GABA transporter on the surface of a cell, which comprises contacting a mammalian cell which comprises a plasmid adapted for expression in a mammalian cell which plasmid further comprises DNA which expresses a human betaine/GABA transporter on the cell's surface with a plurality of compounds, determining those compounds which bind to the human betaine/GABA transporter expressed on the cell surface of the mammalian cell, and thereby identifying compounds which interact with, and specifically bind to, the human betaine/GABA transporter.
20. 35. 35.

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64. The method of claim 63, wherein the mammalian cell is a non-neuronal cell.

65. A method for determining whether a compound not known to be capable of specifically binding to a human betaine/GABA transporter can specifically bind to a human betaine/GABA transporter, which comprises preparing a cell extract from mammalian cells, which comprise a plasmid adapted for expression in a mammal, which plasmid further comprises DNA which expresses a human betaine/GABA transporter on the cell's surface, isolating a membrane fraction from the cell extract, incubating the compound with the membrane fraction under conditions permitting binding of ligands known to bind to the human betaine/GABA transporter, detecting the presence of any bound compound, and thereby determining whether the compound is capable of specifically binding to the human betaine/GABA transporter.

66. The method of claim 65, wherein the mammalian cell is a non-neuronal cell.

67. A method for screening compounds to identify drugs that interact with, and specifically bind to, a human betaine/GABA transporter, which comprises preparing a cell extract from mammalian cells, which comprise a plasmid adapted for expression in a mammalian cell which plasmid further comprises DNA, which expresses a human betaine/GABA transporter on the cell's surface, isolating a membrane fraction from the cell extract, incubating the membrane fraction with a plurality of compounds, determining those compounds which interact with and bind to the human betaine/GABA transporter, and thereby identifying compounds

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- which interact with, and specifically bind to, the human betaine/GABA transporter.

68. The method of claim 67, wherein the mammalian cell is a non-neuronal cell.

69. A method for identifying a compound which is not known to be capable of binding to the human betaine/GABA transporter activates the human betaine/GABA transporter on the surface of a mammalian cell or prevents a ligand which does so, which comprises contacting a mammalian cell which cell comprises a plasmid adapted for expression in the mammalian cell such plasmid further comprising DNA which expresses the human betaine/GABA transporter on the cell surface of the mammalian cell with the compound, determining whether the compound activates the human betaine/GABA transporter or prevents a ligand which does so, and thereby identifying the compound as a compound which interacts with, and activates the human betaine/GABA transporter or prevents the activation of the human betaine/GABA transporter by a ligand which does so.

70. A compound identified by the method of claim 61, 65 or 69.

71. A pharmaceutical composition of a drug identified by the method of claim 63, 67 or 69.

72. A method for detecting the presence of a human betaine/GABA transporter on the surface of a cell, which comprises contacting the cell with an antibody of claim 43, under conditions that permit binding of the antibody to the transporter, detecting the presence of any of the antibody

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bound to the cell, and thereby the presence of a human betaine/GABA transporter on the surface of the cell.

5. 73. A method for treating an abnormal condition related to an excess of activity of a human betaine/GABA transporter, which comprises administering a patient an amount of a pharmaceutical composition of claim 71, effective to reduce betaine/GABA transporter activity as a result of naturally occurring substrate binding to and activating the betaine/GABA transporter.

74. The method of treating abnormalities which are alleviated by an increase in the activity of a betaine/GABA transporter, which comprises administering a patient an amount of a pharmaceutical composition of claim 71, effective to increase the activity of the betaine/GABA transporter thereby alleviating abnormalities resulting from abnormally low transporter activity.

75. A method for diagnosing a predisposition to a disorder associated with the expression of a human betaine/GABA transporter allele which comprises:

- a. obtaining DNA from subjects suffering from a disorder;
- 10 b. performing a restriction digest of the DNA with a panel of restriction enzymes;
- c. electrophoretically separating the resulting DNA fragments on a sizing gel;

d. contacting the gel with a nucleic acid probe capable of specifically hybridizing to DNA encoding a human betaine/GABA transporter and labelled with a detectable marker;

- 5 e. detecting the labelled bands which have hybridized to the DNA encoding betaine/GABA transporter, labelled with the detectable marker to create a unique band pattern specific to the DNA of subjects suffering with the disorder;
 - f. preparing DNA for diagnosis by steps a-e;
- 15 9. comparing the unique band pattern specific to the DNA of patients suffering from the disorder from step e and DNA obtained for diagnosis from step f to determine whether the patterns are the same or different and to diagnose thereby predisposition to the disorder if the patterns are the same.
- 20 15 76. The method of claim 75, wherein a disorder is associated with the expression of a specific human betaine/GABA transporter allele is diagnosed.
- 25 20 77. A method of identifying a substance capable of alleviating the abnormalities resulting from overexpression of a human betaine/GABA transporter which comprises administering a substance to the transgenic non-human mammal of claim 61 or 60, and determining whether the substance alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of

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overexpression of the human betaine/GABA transporter.

78. A method of identifying a substance capable of alleviating the abnormalities resulting from underexpression of a human betaine/GABA transporter, which comprises administering a substance to the transgenic mammal of claim 55, and determining whether the substance alleviates the physical and behavioral abnormalities displayed by the transgenic nonhuman mammal as a result of underexpression of the human betaine/GABA transporter.

5 79. A method of treating abnormalities in a subject, wherein the abnormality is alleviated by the reduced expression of a human betaine/GABA transporter which comprises administering to a subject an effective amount of the pharmaceutical composition of claim 47, 49 or 71 effective to reduce expression of the human betaine/GABA transporter.

10 80. A method of treating abnormalities resulting from underexpression of a human betaine/GABA transporter which comprises administering to a subject an amount of a pharmaceutical composition of claim 48 or 71 effective to alleviate abnormalities resulting from underexpression of the human betaine/GABA transporter.

15 81. An expression vector of claim 7 adapted for expression in an insect cell which comprises the regulatory elements necessary for expression of the DNA encoding a betaine/GABA transporter in the bacterial cell operatively linked to the cDNA

encoding the betaine/GABA transporter as to permit expression thereof.

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82. A method for screening compounds to identify drugs that interact with, and specifically bind to, a human betaine/GABA transporter, which comprises preparing a cell extract from insect cells, which comprise an expression vector adapted for expression in an insect cell which vector further comprises DNA which expresses a human betaine/GABA transporter on the cell's surface, isolating a membrane fraction from the cell extract, incubating the membrane fraction with a plurality of compounds, determining those compounds which interact with and bind to the human betaine/GABA transporter, and thereby identifying compounds which interact with, and specifically bind to, the human betaine/GABA transporter.

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FIGURE 1A

FIGURE 1A
FIGURE 1B
FIGURE 1C
FIGURE 1D

<pre> -200 -180 -160 TTGGGACTCTCTGGAGACCTGTGGCCACAGCCAAAGCTGACCACAGGGGGCTGGCTGG -140 -120 -100 GGACTGAGGGAAACTTAAGCTTCAGGAGGGGCTGTGATTGGCTGAGGTCAACAGCAA -80 -60 -40 CTTAGAGACCCAGCTCCACGACTCATGTCTGGCTTGGCCCTCGTCATCTGCCAAC -20 0 20 CAGGGGGGTTCCAACCCACACAGCAAGCCATGGGGGGAAAGGGGGCTGTGCAAGAGPAT H D G K V A V Q E Y </pre>	<pre> 40 60 80 GGGGGCTCTGGAGCTCTCTGGGTCCCCGGAGGGAGGAGAAGCTGGACCAAGGAAGAGAC G P P A V S W V P E E G E K L D Q E D E </pre>	<pre> 100 120 140 GACCAGGGTGAAGATCTGGGGCAATGGGCAACAGAGATGGAGTGTGGGGCTGAGAGAG D Q V K D R G Q H T N K M E P V L S V A </pre>	<pre> 160 180 200 GGGGAGATCATGGGCTCTCTCATCCCGCATGGGGTTCCTCATCTGCTAACAAAACCGA G E I I G L G N V W R P P Y L C Y K N G </pre>	<pre> 220 240 260 GGGGAGCCCTCTCTCATCCCGCATGGGGTTCCTCATCTGCTAACAAAACCGA G G A P P I P Y F P V C G I P V F </pre>	<pre> 280 300 320 TTCTGGAGCTGGGGCAATAACCCAGGAAAGGGACTCTCACAGCCTGGGAAAG F L E V A L G Q Y T S Q G S V T A W R K </pre>	<pre> 340 360 380 ATCTGGCCCCCTCTCCAGGGCATTTGCTGGCATCTGTGGTCAATGGCTATTTGAACT I C P L F Q G I G L A S V V I E S Y L N </pre>	<pre> 400 420 440 </pre>
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FIGURE 1B

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V Y I I L A W A L F Y L F S S P T S	460	480	500	
GAGCTGCCTGGACGACTGGCAAACAACTTTGGAACACAGGCAATTGACCGACTTTCACCTGTCTACCTGTCAGCTCCTTCACCTCT	E L P H T T C N N F W N T E H C T D F L	520	540	560
AACCACTAAGGGCCGACAGTGACCCCCATTGGACRATTTTACCTCACCTGTCTACCTGTCTACGGAA	N B S G A C T V T P F E N F T S P V M E	580	600	620
TTCCTGGGAGAGGAGCTGGGATCATCCCTGGGATCCATGCCCTGGGCTCCCTGGGAG	F W E R R V L G I T S G I H D L G S L R	640	660	680
TGGGAGCTGGCCCTGTCCTGGCCCTGGGCTCATCTGGCTATTCGCTATTCTGGCATCTGGAG	W E L A L C L L A W V I C Y P C I W R	700	720	740
GGGGTCAACTCCACAGGCAAGGGTGGTTTATTTCACACCCACCGTTCCGTACCTGTATGGCT	G V K S T G K V V Y P T A T P Y L M L	760	780	800
GTCATTTCTGTATGAGGGTGTCAACCTTCGGAGCTTACCAAGGGCATCATCTACTAC	V I L L I R G V T L P G A Y Q G I I Y Y	820	840	860
TITGAAGCCAGATTTCGTCGGCCCTCAAGGACCCCTCAAGGCTGGATGGATGGGACCCAG	L K P D L P R L K D P Q V W M D A G T Q	880	900	920
ATCTTCTCTCCCTGGCATCTGCCACGGCTGCCCTGACAGCCCTGGGAGCTACAAACAGC	I F F S P A I C Q G C L T A L G S Y N K	940	960	980
TATCACAAACACTGTACAGGACTGGCTGGATGGCTCCATCTGGCCCTCATGTCACAGTGGCCACCCAG	Y H N N C Y K D C I A L C F L N S A T S	1000	1020	1040
TTTGTGGCTGGCTGGTTGTCCTCTCCCATCTGGCCCTCATGTCACAGGCAAGGGCTC	F V A G P V V F S I L G F M S Q E Q G V			

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FIGURE 1C

P P R Q L R K S G R E L L I T A V	T T T C C C A G C G T C C G A A G G C G G C C G C T C C T C A T C C T C A C C A T G C C G T C	1240	1260	1280	1320	1340

P D Y A S S G I C L L U P L S L P E V V
 1420 1440 1460
 TGTGATAAAGCTGGCTATGGGGACCGTTCTATGACAACATTGAGGACATGATTGGC
 C I S W V Y G A D R P Y D N I E D M I G

Y R P W P L V K - I S . W L P L T P G L C L	1480	1500	1520
	1540	1560	1580

A A T P L F S L S K Y T P L K Y N N V V	TACCCGCTGGGATTAATCCATTGGTTCCTGGCTCATGGCTGTGTC Y P P W G Y S I G W P L A L S S H V C V
1600 1620 1640	

WFO 96/04790

CTUS95/10579

W0 96/04790

PC7US95J10579

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FIGURE 2A
FIGURE 2B
FIGURE 2C
FIGURE 2D
FIGURE 2E
FIGURE 2F
FIGURE 2G

FIGURE 2A

תְּמִימָנָה - י

האגט - 1
DBCT - 1
טBgT - 1
טBgT - 2
טBgT - 3

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RGA
RGS
DBW
DBP
DB4

• 16

AVEDO
AVEDO
AVEDO
AVEDO
AVEDO
AVEDO
AVEDO
AVEDO
AVEDO
AVEDO

100 E A S Y V I E S X L K V Y Y I I I L A H U A I
101 G I G L A S A V E S Y L M A Y T E I I L A H U A I
102 G I G H A Y S E V I E S S Y L H I T Y I I L A H U A I
103 G I G Y A D O V I E H R V Y Y I I I L A H U A I
104 G I G Y A S P H I V S L L A H U A I
105 G I G Y A S P H I V S L L A H U A I
106 F A L I S S E I S E P U T I C I N S W M T E H C
107 F A L I S S E I T M E L P U T I C I N S W M T E H C
108 F A L I S S E I T I D O I P U G S C S H E W H T E N C
109 F A L I S S E N C F T T E I P U A I C G H E U N T E K C
110 F A L I S S E T I S S E I S E P U T I C I N S W M T E H C
111 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
112 F A L I S S E T I S S E I T I D O I P U G S C S H E W H T E N C
113 F A L I S S E T I S S E I T I D O I P U G S C S H E W H T E N C
114 F A L I S S E T I S S E I T I D O I P U G S C S H E W H T E N C
115 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
116 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
117 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
118 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
119 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
120 F A L I S S E T I S S E I T M E L P U T I C I N S W M T E H C
121 G I G L A S A V E S Y L M A Y T E I I L A H U A I
122 G I G H A Y S E V I E S S Y L H I T Y I I L A H U A I
123 G I G Y A D O V I E H R V Y Y I I I L A H U A I
124 G I G Y A S P H I V S L L A H U A I
125 G I G Y A S P H I V S L L A H U A I
126 H D F L I N H S . G A R T A T S S E H F T S P V N E
127 H D F L I N H S . G A C T V I P F E N E F T S P V N E
128 H D F L I N H S . S A R G A S S S E M F T S P V N E
129 H D F L I N H S . E H A T S S P V I E
130 H D F L I N H S . M S L H V T S . E H A T S S P V N E
131 H D F L I N H S . O K I H . M S L H V T S . E H A T S S P V N E
132 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
133 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
134 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
135 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
136 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
137 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
138 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
139 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E
140 H D F L I N H S . V E E F O K L H F S H A S L O N A T S P A H E

FIGURE 2B

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FIGURE 2C

hBGT-1	F W E R R V E G I T S G F H D L G S E R W E E A E	
dBGT-1	F W E R R V E G I T S G E H D E G A E R W E E A E	
mBGT-1	F W E R R V E G I T S G E H D E G S E R W E E A E	
rGAT-2	F W E R R V E K I S D G T O H L G S E R W E E V E	
rGAT-3	F W E R R V E A I S D G E E H I G N E R W E E A E	
	IV	
	C L E L A U V I C Y F C I W K G V K S T G K V V Y	240
	C L E L A U L I C Y F C I W K G V K T T G K V V Y	240
	C L E L A U I I C Y F C I W K G V K S T G K V V Y	240
	C L E L A U I I C Y F C I W K G V K S T G K V V Y	235
	C L E L A U I I C Y F C I W K G T K S T G K V V Y	250
	V	
hBGT-1	F T A T F P Y L M E V I L L I R G V T L P G A Y Q	
dBGT-1	F T A T F P Y L M E V I L L I R G V T L P G A Y Q	
mBGT-1	F T A T F P Y L M E V I L L I R G V T L P G A Y Q	
rGAT-2	F T A T F P Y L M E V I L L I R G V T L P G A A Q	
rGAT-3	V T A T F P Y I M E L L I R G V T L P G A S E	
	G F E F Y E L K P D E F R L K D P C V W H D A G T Q	290
	G V E Y Y I L K P D E L R L K D P G V W H D A G T Q	290
	G E V F Y L K P D E L R L K D P O V W H D A G T Q	290
	G E O F Y E L Y P H I T R L W D P C V W H D A G T Q	285
	G E K F Y L Y P D L S R L S D P G V U V D A G T Q	300

FIGURE 2D

hBGT-1	I F F S F A I C Q G C E F A L G S Y N K T H H H C	
dBGT-1	I F F S F A I C Q G C E F A L G S Y N K Y H H H C	
mBGT-1	I F F S F A I C Q G C E F A L G S Y N K Y H H H C	
rGAT-2	I F F S F A I C L G C L T A L G S Y N K Y H H H C	
rGAT-3	I F F S T A F C L G C E T A L G S Y N H Y H H H C	
	VI	
	T K D C E A L C F E N S A T S E V A G E V V V E S I	340
	T R D S I A E C F E N S A T S F A A G E V V V E S I	340
	T R D S T A E C F E N S A T S F V A G E V V V E S I	340
	T R D C V A L C I E N S S T S F V A G E A I F S I	335
	T R D C I M E C C L N S G T S E V A G E A I F S V	350
hBGT-1	L G F M S Q E O G V P I S E V A E S G P G L A F I	
dBGT-1	L G F M A Q E Q Q G L P I S E V A E S G P G L A F E	
mBGT-1	L G F M S Q E O G G I P I S E V A E S G P G L A F I	
rGAT-2	L G F M S Q E Q Q G V P I S E V A E S G P G L A F I	
rGAT-3	L G F M A Y E O G V P I A E V A E S G P G L A F S	
	VII	
	A F P K A V T H M P L S O L W S C L F F I N L I F	390
	A F P K A V T H M P L S G L W S C L F F I N L I F	390
	A F P K A V T H M P L S G L W S C L F F I N L I F	390
	A Y P R A V V N L P F S P L W A C C E F F H V V L	385
	A Y P K A V T M M P L S P L W A T L F F M H L I F	400

FIGURE 2E

hBGT-1 EGEDSQFVVCVECLVTASIDONHFPRL
 dBGT-1 LGLOSQFVYCYECLVTASHDHFPSQL
 mBGT-1 LGLDSDQFVCHECCLVTASHUHFPPQL
 rGAT-2 LGLOSQFVCEVESLYTALVDHYPRVF
 rGAT-3 LGLDSDQFVCEVESLYTAVVUDHYPKVF

 IX
 RKS GRRRELLITLTIAVMHCYLTIGELFLV 440
 RKS GRRRELLILAIAYFCYLAGEFLV 440
 RKS GRRRDVLILAIATSVLCYLHGLLIV 440
 RKKNRRREILILIVSYVSFIGIIML 435
 RRGYRRELLIEALSIVSYFLGEVML 450

hBGT-1 TEGGNYIFQLEFDYTASSGICLIFLS
 dBGT-1 TEGGNYIFQLEFDYTASSGICLIFLA
 mBGT-1 TEGGNYIFQLEFDYTASSGICLIFLS
 rGAT-2 TEGGNYVFOLEFDYTASSGMCLIFVA
 rGAT-3 TEGGNYIFQLEFDSYAASGMCLIFVA

 X
 LFEVICISWVYGADEFYDNIEDMIG 490
 MFEVICISWVYGADEFYDNIEDMIG 490
 LFEVICICIGHVYGADEFYDNIEDMIG 490
 IFEESLCAVAVVYGAESRFYDNIEDMIG 485
 IFECCVCGWVYFGSNRFYDNIEDMIG 500

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FIGURE 2F

hBGT-1 YRPWPLVKISWLFLTPGLCLATEFLF
 dBGT-1 YRPWPLVKISWLFLTPGLCLATEFLF
 mBGT-1 YRPWPLVKISWLFLTPGLCLATEFFF
 rGAT-2 YKWPWPLVKYCWLTFTPAVCLATEFLF
 rGAT-3 TRPLSLIKWCWKVVTPGICAGIFIF

 XI
 SELSKYTFPLKYNNVVVYPPWPGYSIGW 540
 SELSKYTFPLKYNNVVVYPPWPGYSIGW 540
 SELSKYTFPLKYNNVVVYPPWPGYSIGW 540
 SELIKYTFPLTYNKKTYPWUNGDALGW 535
 FLVKYTFPLKYNNVVVYTPAWGYGIGGW 550

XII
 hBGT-1 FLALSSNVVCVPLFVVIITLEKTRGPFF
 dBGT-1 FLALSSHVICVPLFYIITLLEKTRGSF
 mBGT-1 LLAFSSMACVPLFIITFLKTOGSF
 rGAT-2 LLALSSSHVCIPAWSIYKERTLKGPL
 rGAT-3 LMALESSHLCIPLWIFIKLWKTEGTL

 KKRLRQLITPDSSLPOPQKQ.HPCLD 589
 KKRLRQLTTPDPSLPOPQKQ.HLYLD 589
 KKRLRRLITPDPSLPOPQGR.RPPQD 589
 RERIRQEVCPAEDLPQKSQ..... 579
 PEKLOKLTVPSADLKMRGKLGASPR 600

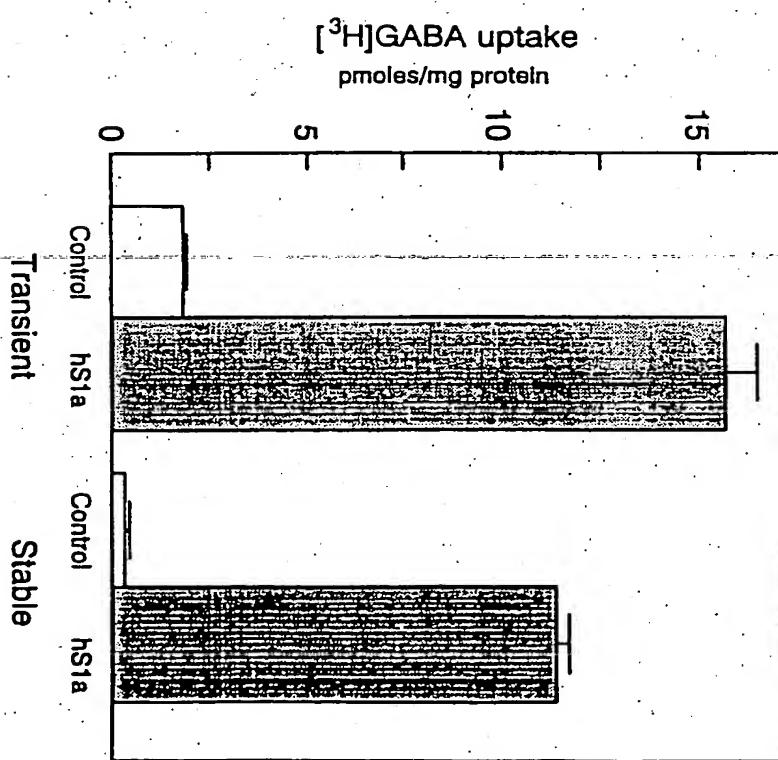
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FIGURE 2G

hBGT-1	G S A G R M F G P S P T R E G E L I . . . A G E K E T H E	614
dBGT-1	G G T S Q D C G P S P T K E G E L I . . . V G E K E T K E	616
rBGT-1	G S S A Q N C C S S P A K G E L I . . . A U E K E T H L	614
rGAT-2	. . . P E L T S P A T P H T S L L R . . . L T E L E S N C	602
rGAT-3	M V T V N O C E A K V K G D G T I S A I T E K E T H F	627

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FIGURE 3



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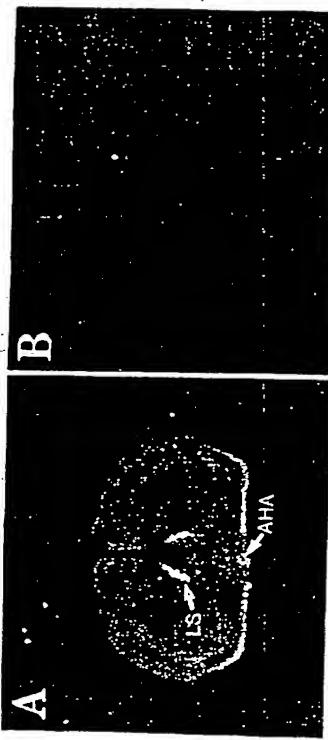
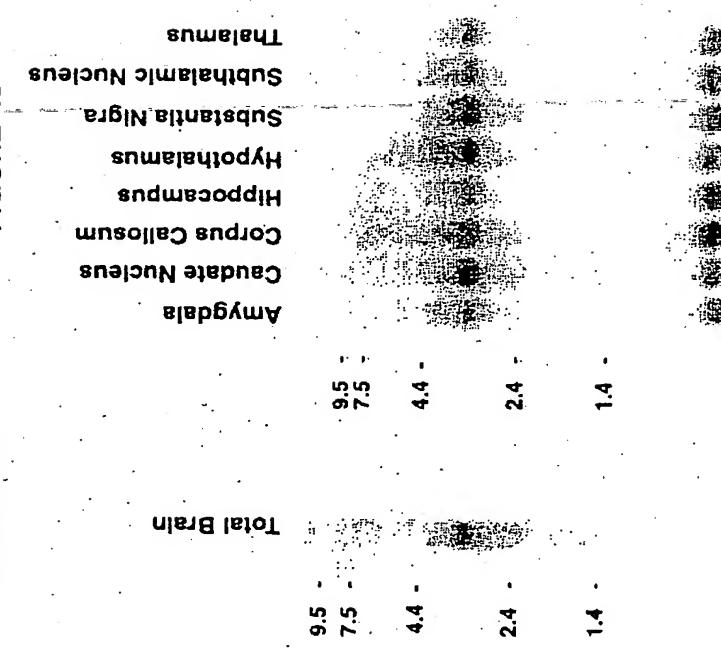
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FIGURE 4A

FIGURE 4B

FIGURE 5A

FIGURE 5B



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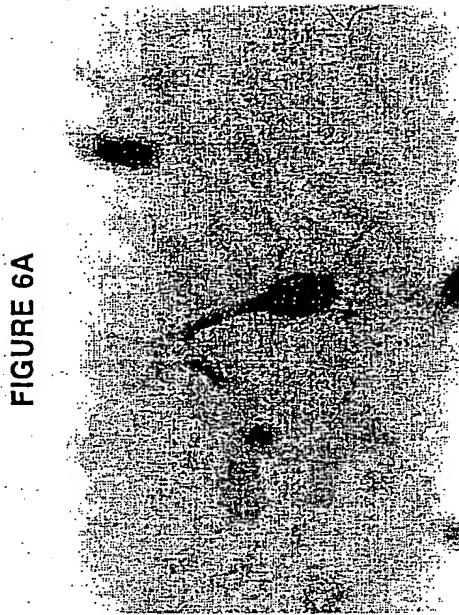
PCT/US95/10579

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FIGURE 5C



FIGURE 5D



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FIGURE 6A

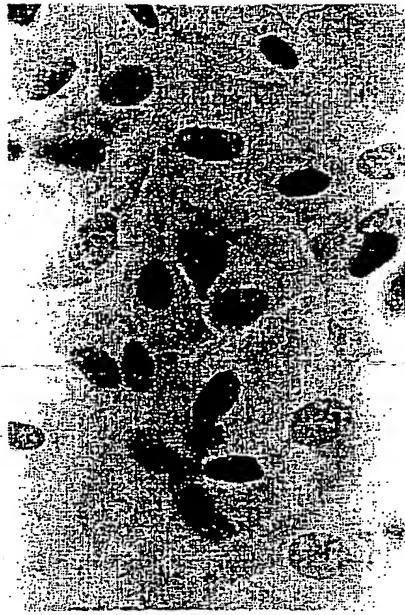


FIGURE 6B

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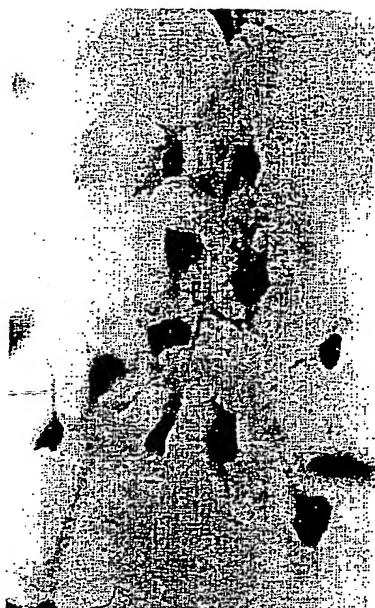
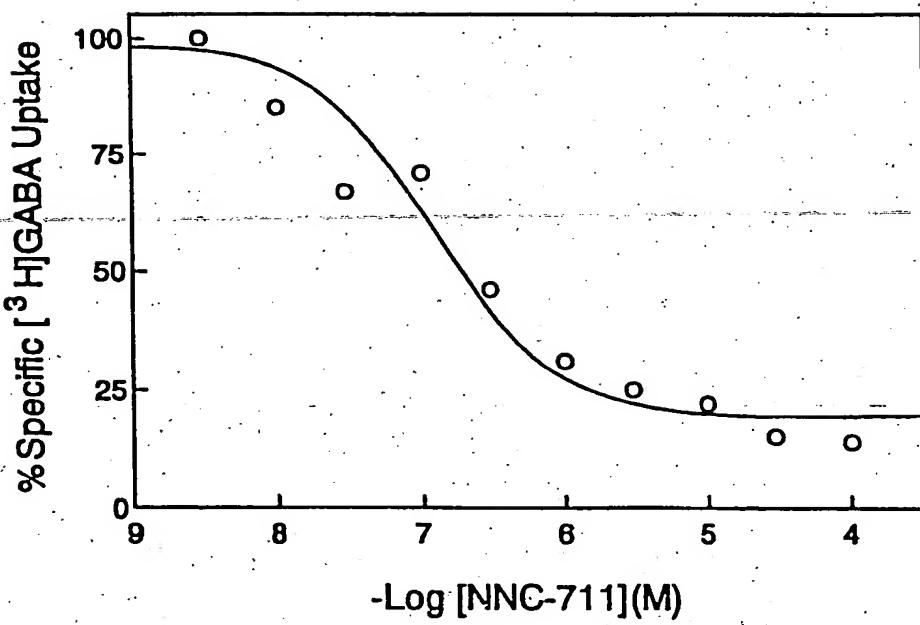
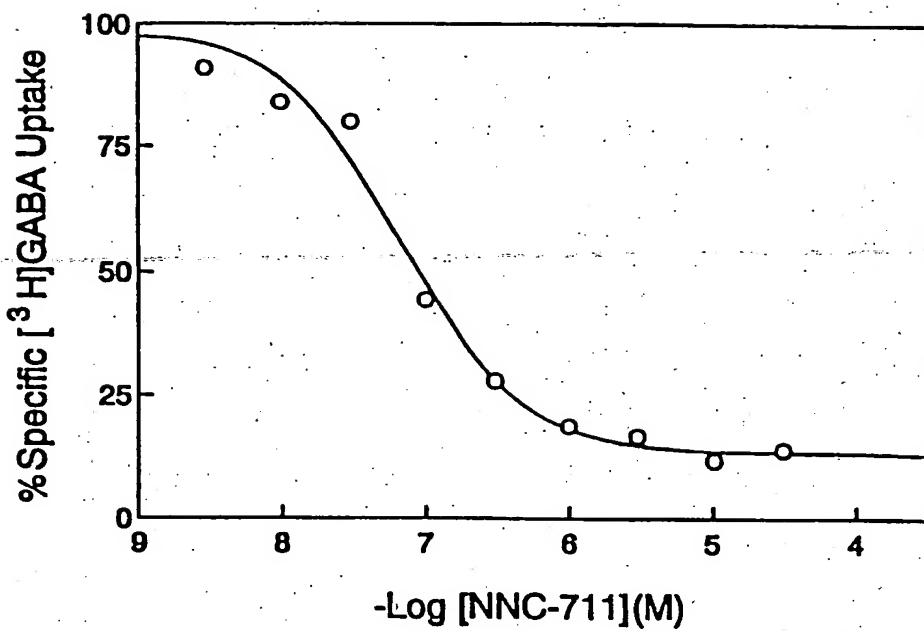
FIGURE 6C**FIGURE 7**

FIGURE 8

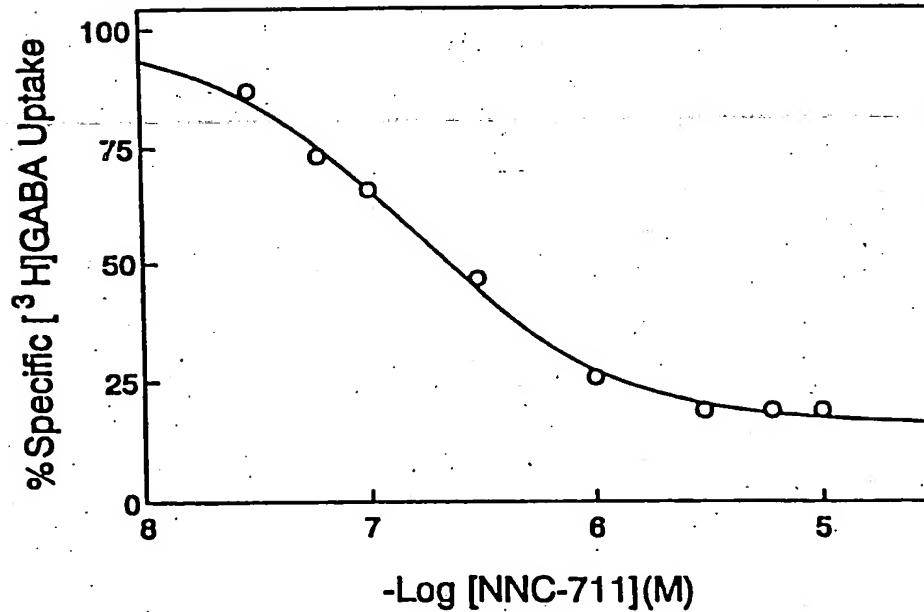


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FIGURE 9



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FIGURE 10

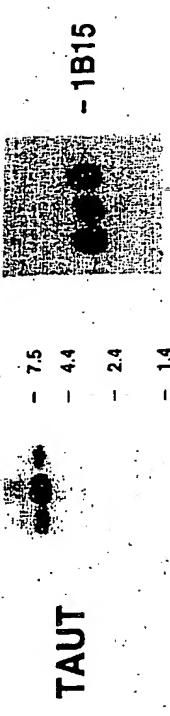
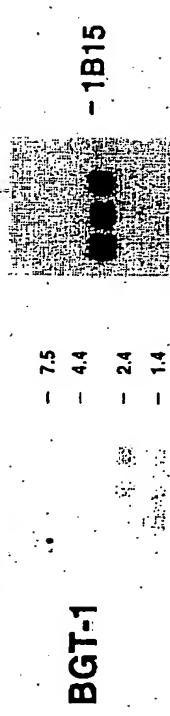
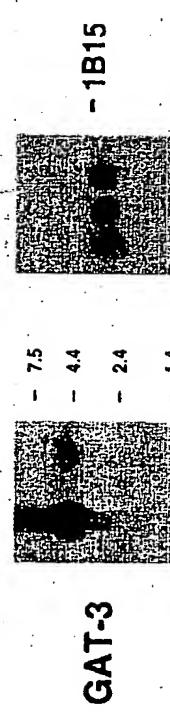
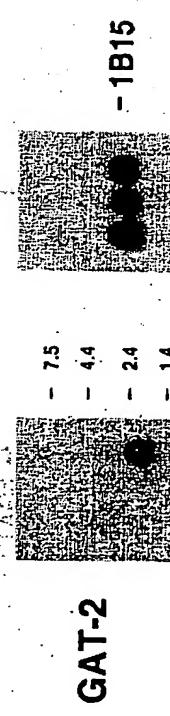
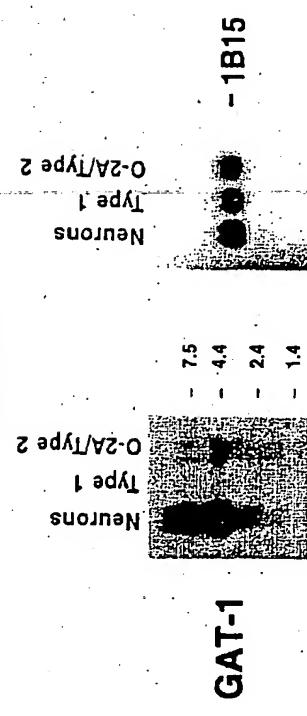
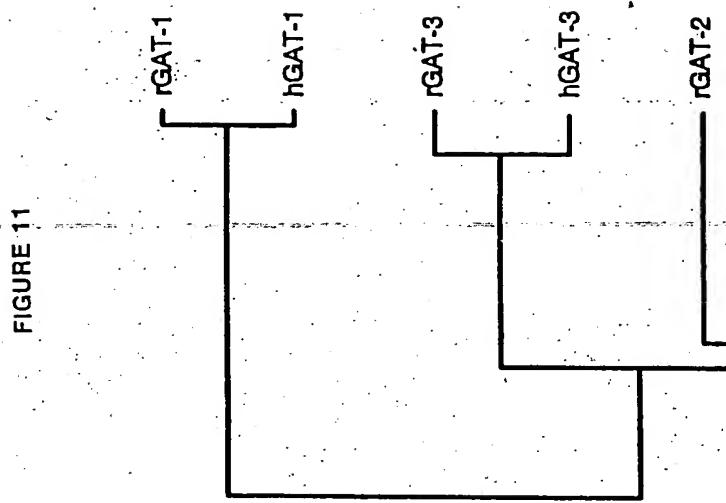


FIGURE 11

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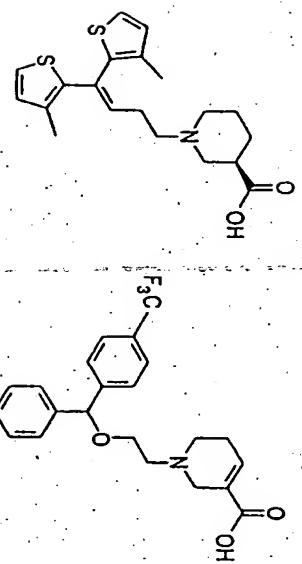


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FIGURE 12

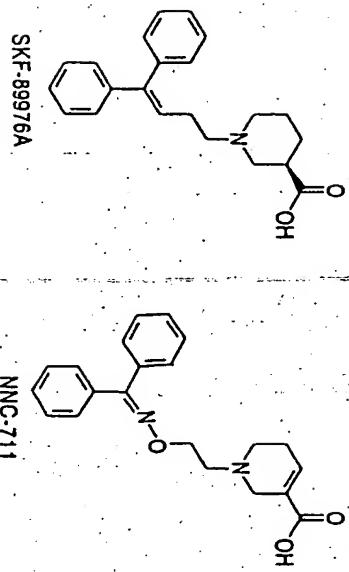


Guvacine



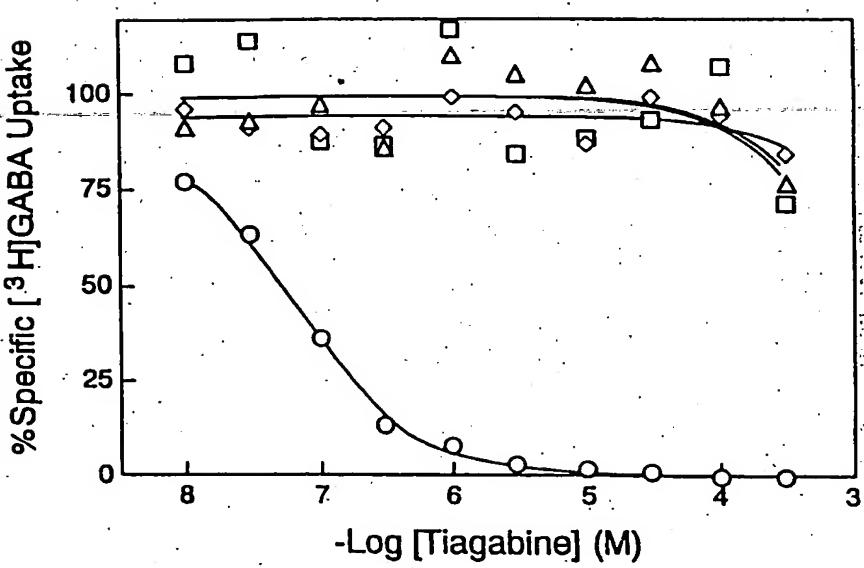
Tiagabine

CI-966



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FIGURE 13



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FIGURE 14

Rat Betaine/GABA Transporter

10	AGCTGTGGTATCCAGTGTTCCTGGGGCTGGACTGGCATATAGCGGCCAGGG
20	S C G I P V F L E V A L G Q Y S S Q G
30	AGCTGTTACITGCCTGGGAGAATCTGTCCTCCTGGCATGGCTCTCTG
40	S V T A W R K I C P L L Q G I G M A S V
50	GTCATCGAGTCCTTCACTTGAACATCTACTACATCATTCTGCCTGGCTCTCTAC
60	V I E S Y L N I Y Y I I I L A W A L F Y
70	CCTTCAGCTCCCTCACCTGGAGCTTCCGGACACCTGCACCACTCCGAACACA
80	L F S S F T W E L P W T T C T N S W N T
90	GAACATTGGTGAACTTCTGAACTACTCATGCCAGGCCGAGCTGAGCTGAGAAC
100	E H C V D F L N Y S S T R A A S Y S E N
110	TTCACCTACCCAGTCATGGAAATTCTGGAGAGACGGTTTGGCTATTACATGGCATT
120	F T S P V M E F W E R R V L G I T S G I
130	CATGACCTGGGGCTCCCTGGCTGGGGCTGGCCCTGCGCTCGCCCTGCGATC
140	H D L G S L R W E L A L C L L A W I
150	160
170	180
190	200
210	220
230	240
250	260
270	280
290	300
310	320
330	340
350	360
370	380
390	400
410	420